

The South Pole Telescope and the Millimeter Sky

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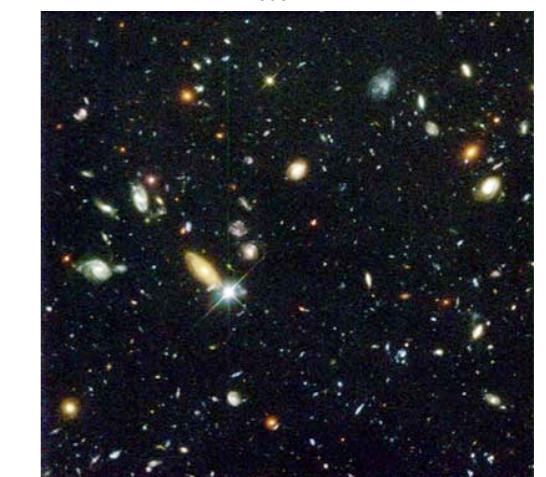
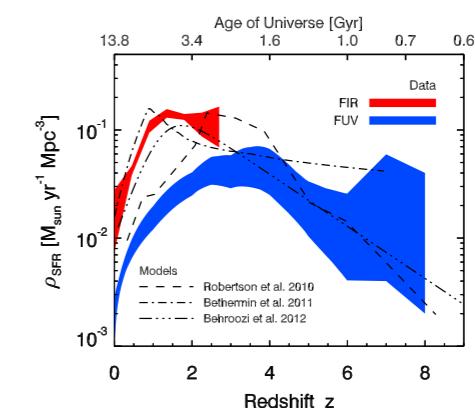
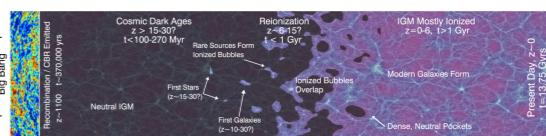
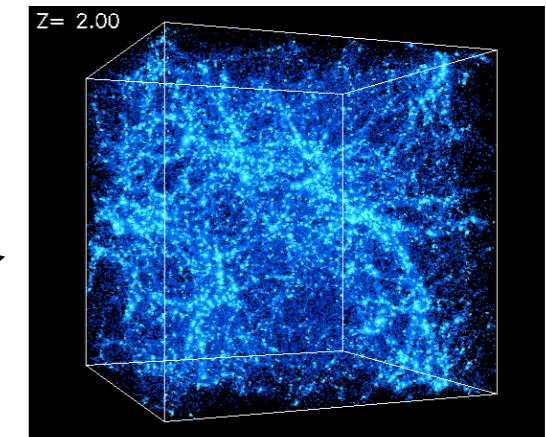
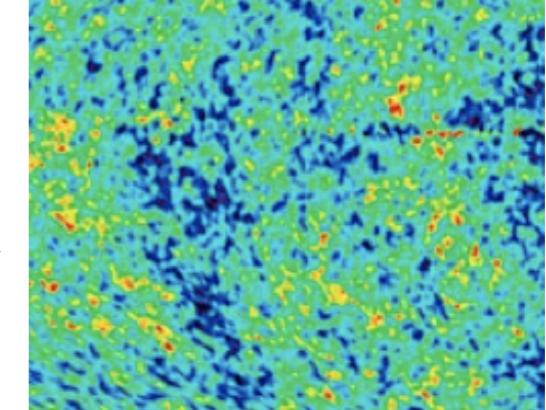
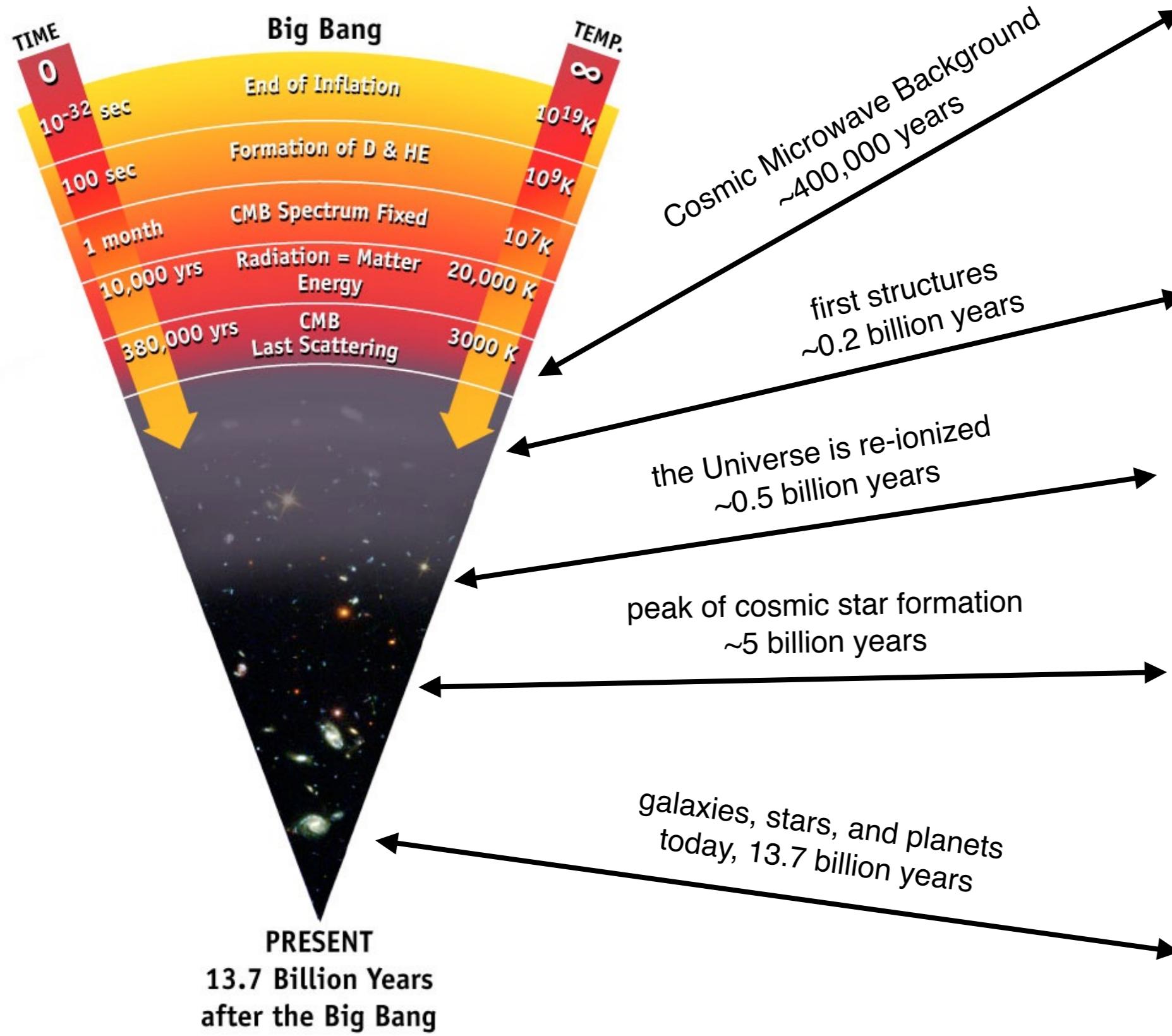
18 Nov 2013



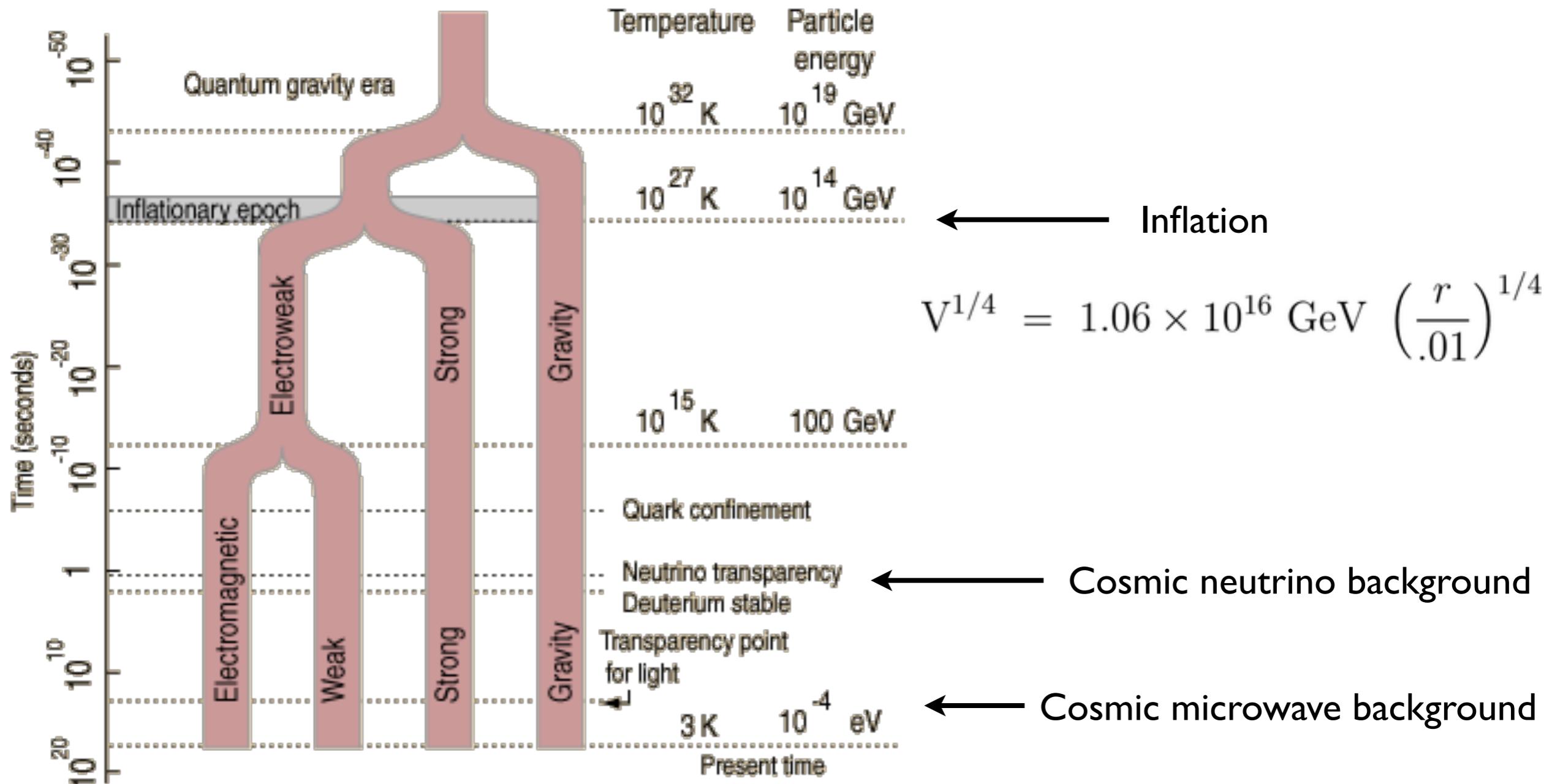
Outline

- General Cosmology Intro
- South Pole Telescope
- Cosmic Microwave Background
- Sunyaev-Zeldovich Galaxy Clusters
- Epoch of Reionization
- Cosmic Infrared Background
- Strongly lensed sources
- CMB lensing
- Polarization

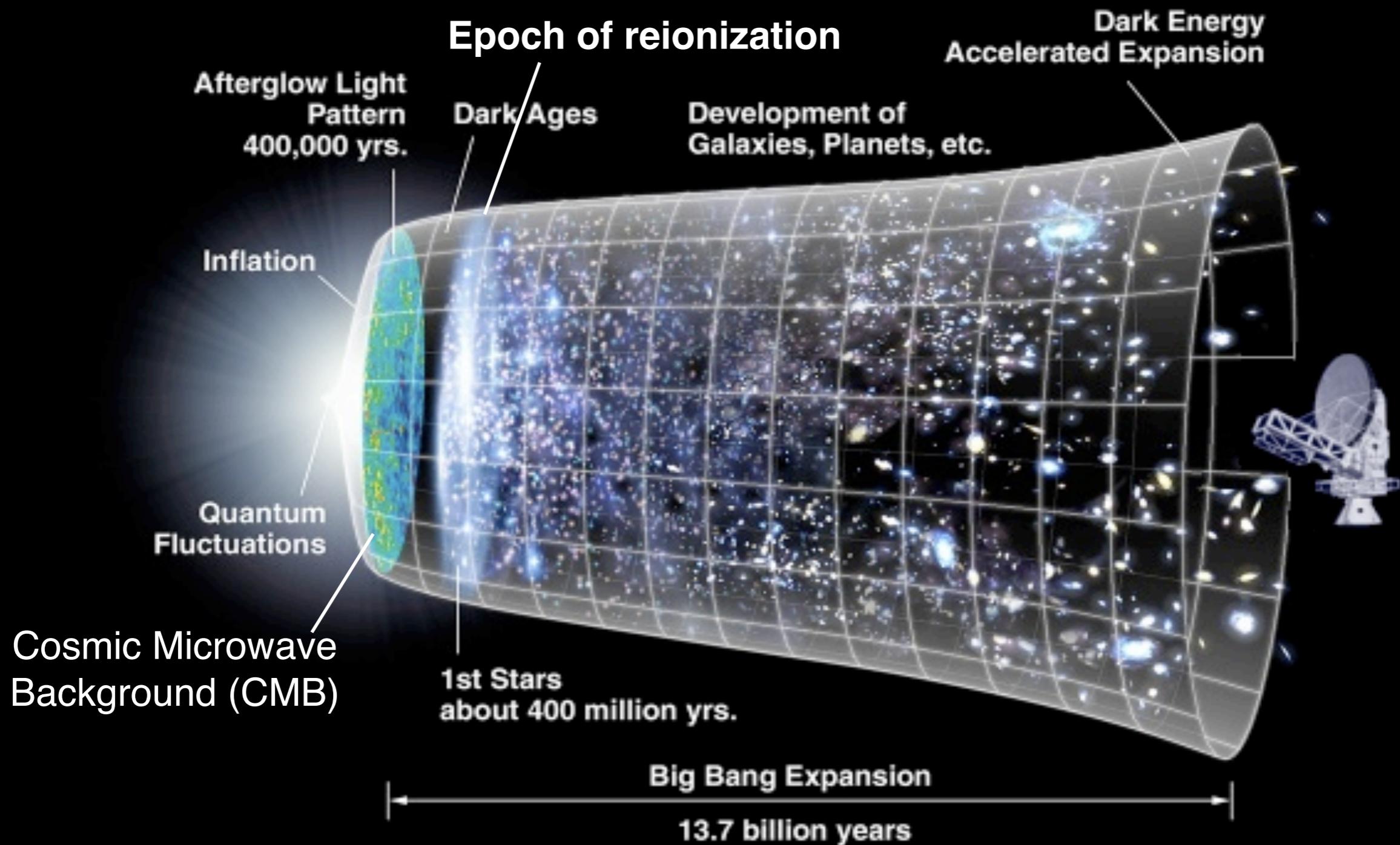
Brief History of the Universe



The early Universe as a HEP lab

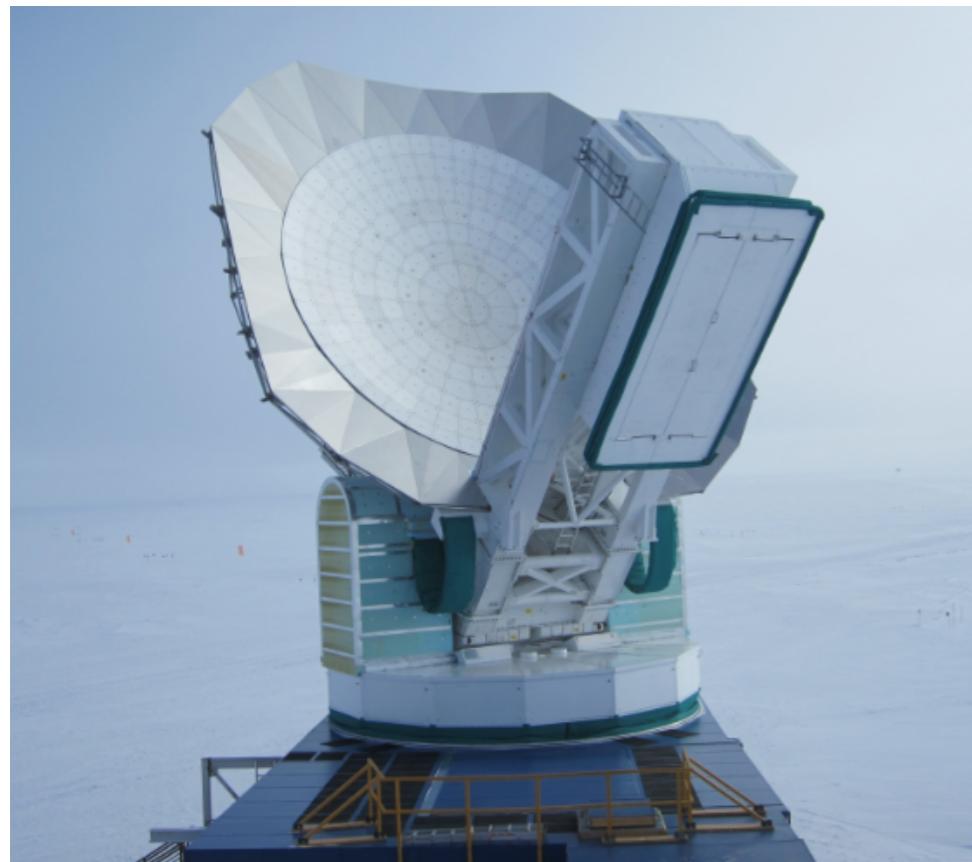


Brief History of the Universe



SPT

The South Pole Telescope



Funded by
NSF

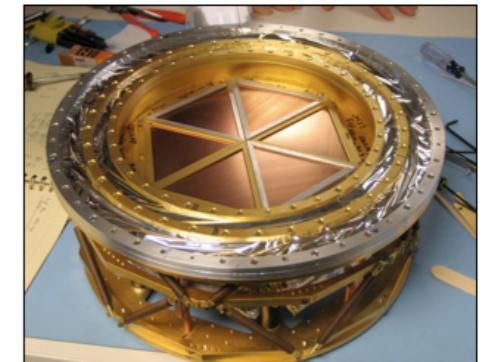


Telescope

- 10 meter off-axis sub/mm telescope
- located at the geographic south pole
- 1 deg² field of view
- ~1' beams
- optimized for fine scale anisotropy measurements

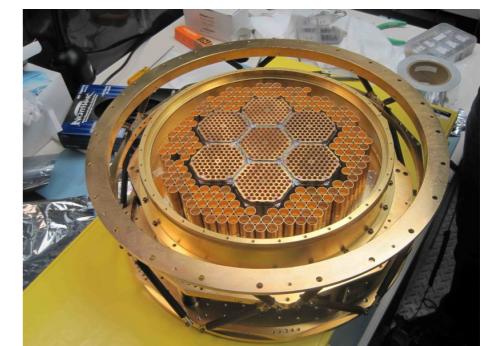
SPT-SZ Camera (1st Generation):

- 2007 – 2011
- 960 pixel mm camera
- 1.4, 2.0, and 3.0 mm
- completed 2500 deg²
- 18 μK-arcmin depth, ~1 mJy



SPT-pol Camera (2nd Generation):

- 2012 – 2015
- 1600 pixel mm camera
- 2 and 3 mm + polarization
- currently surveying 500 deg² x4 deeper
- 4.5 μK-arcmin depth



SPT-3G Camera (3rd Generation):

- 2016 – 2020
- 15k pixel mm camera
- 1.4, 2, 3 mm + polarization
- planned 2500 deg² x8 deeper
- 2.5 μK-arcmin depth





Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO



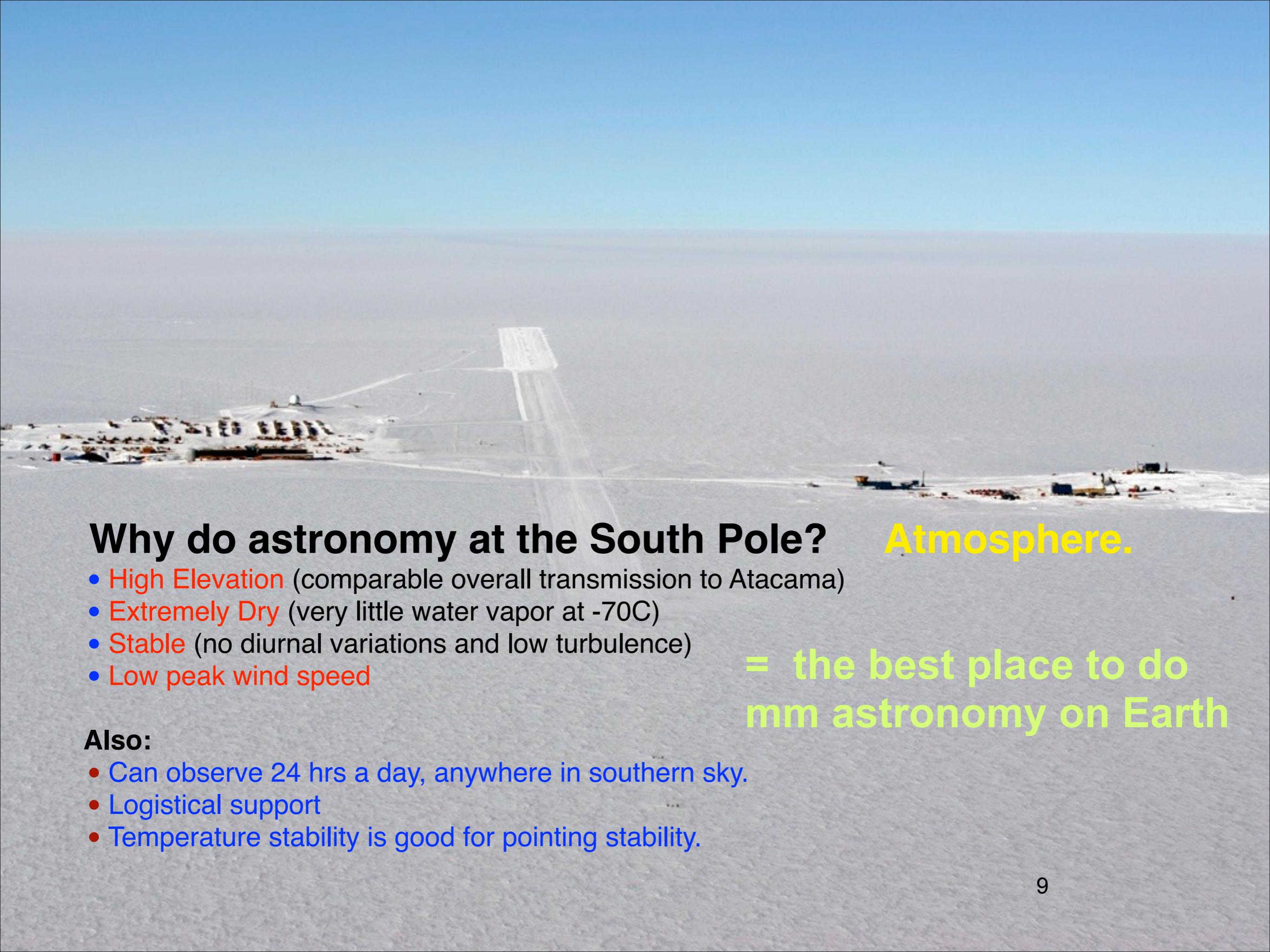
SPT Team February 2007



SPT Team

July 2013





Why do astronomy at the South Pole?

- High Elevation (comparable overall transmission to Atacama)
- Extremely Dry (very little water vapor at -70C)
- Stable (no diurnal variations and low turbulence)
- Low peak wind speed

Atmosphere.

= the best place to do
mm astronomy on Earth

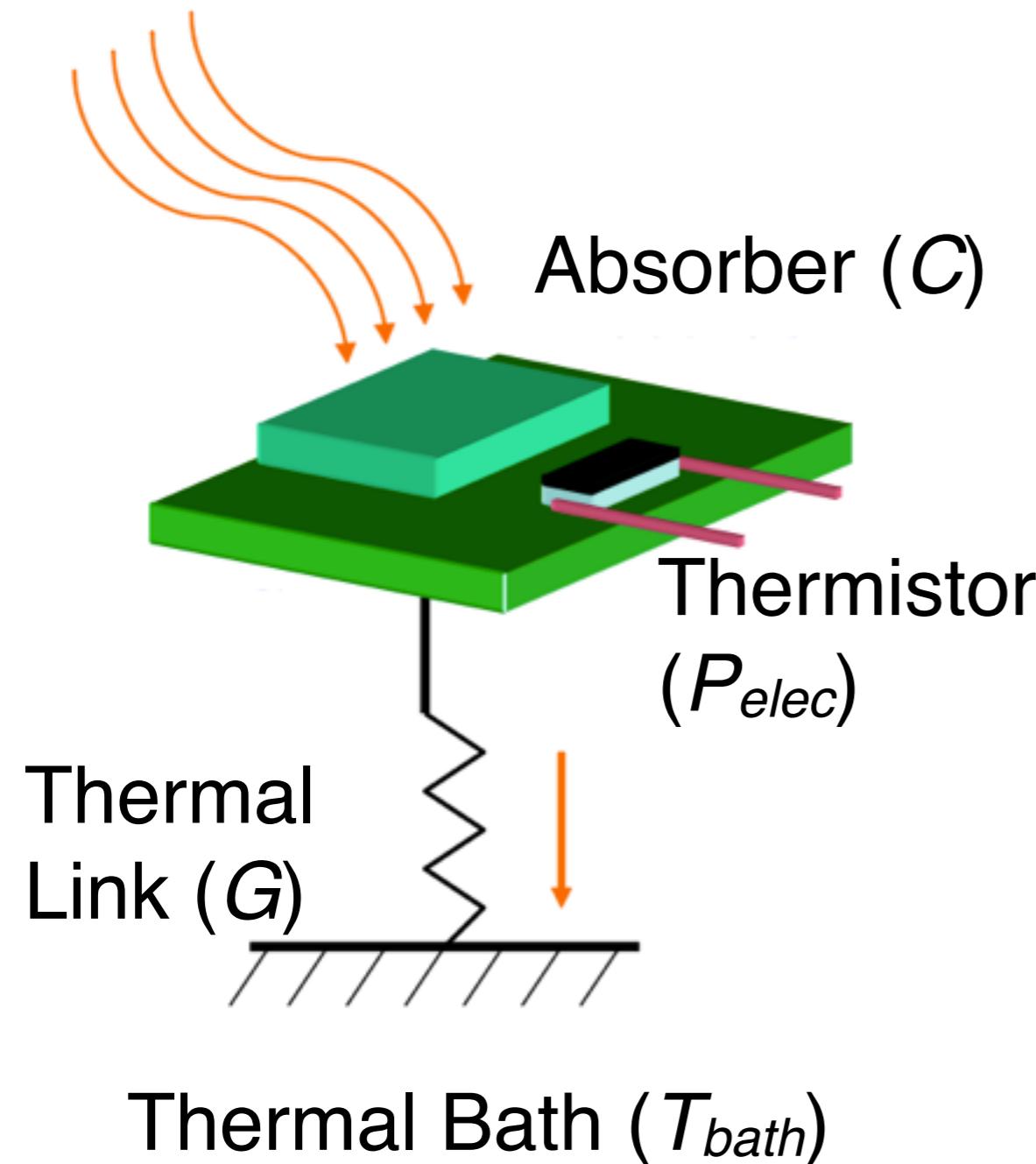
Also:

- Can observe 24 hrs a day, anywhere in southern sky.
- Logistical support
- Temperature stability is good for pointing stability.

Bolometers

A bolometer is the most sensitive mm-wavelength detector

Radiation (P_{opt})



Bolometer Design / Noise Properties:

- Optical Power: P_{opt}
- Thermal Conductivity: $G \sim P_{tot}/dT$
- Heat Capacity: C
- Time Constant: C/G
- Thermal Noise:

$$NEP_G^2 \approx 4kT_c^2 \bar{G}$$

- Photon Noise:

$$NEP_\gamma^2 \approx 2h\nu_0 P_{opt}$$

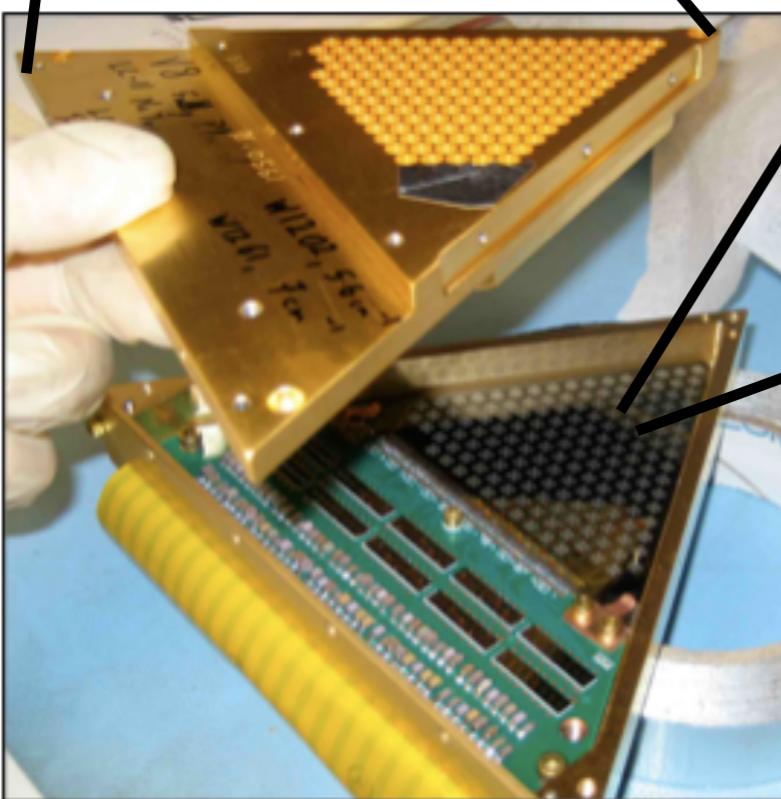
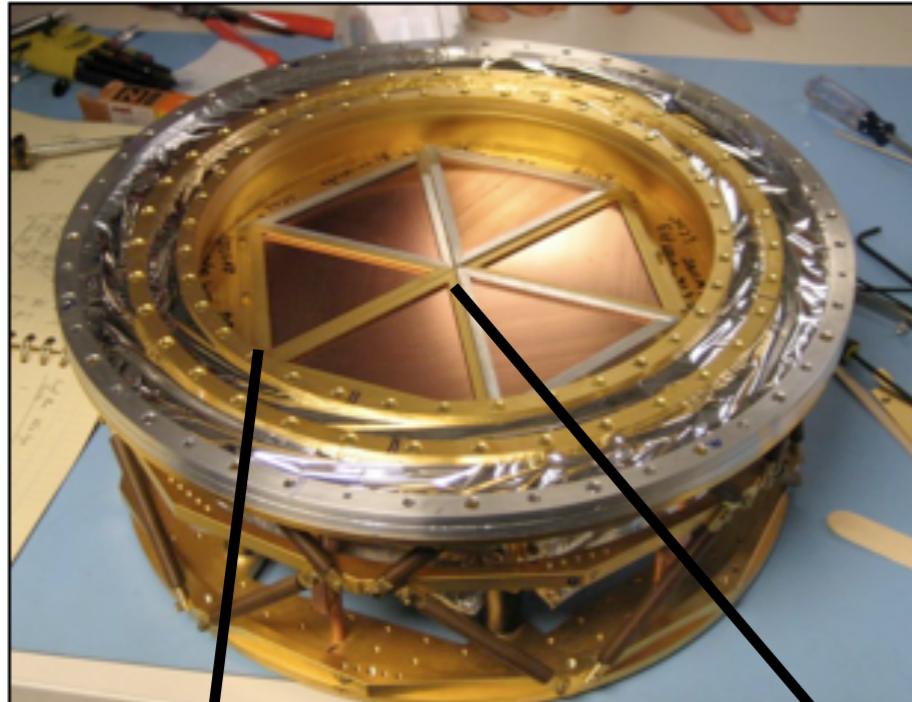
small $G \rightarrow$ more sensitive detectors

small $C \rightarrow$ fast detectors

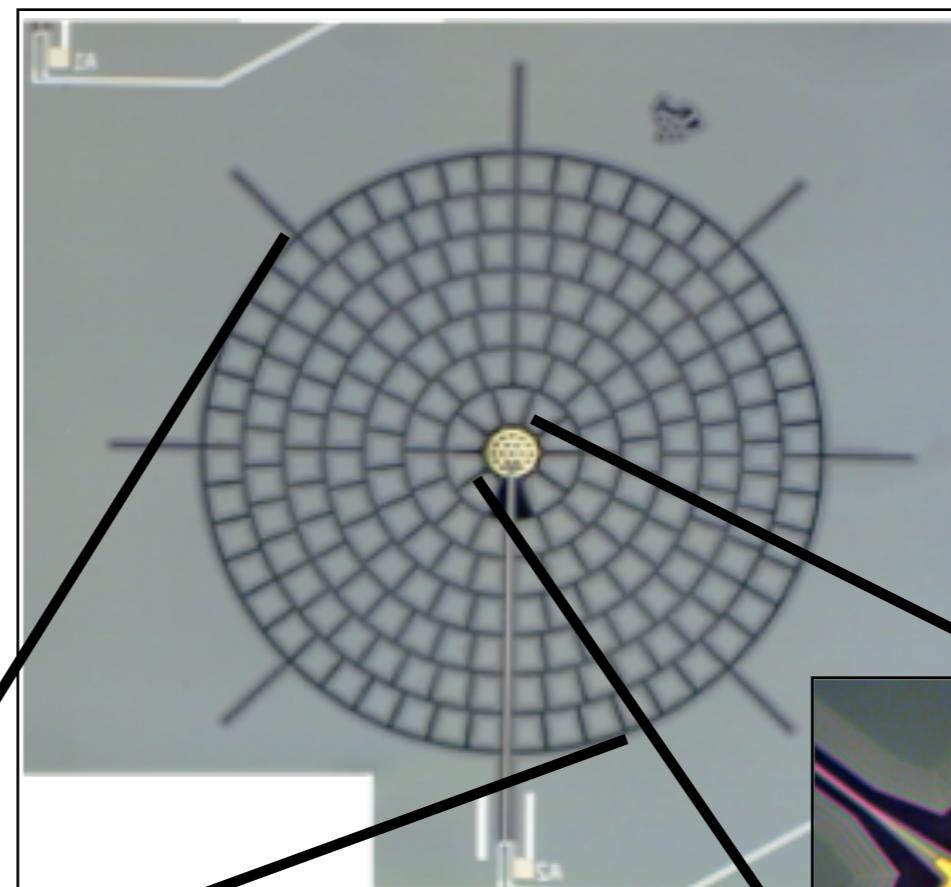
thermal noise < photon noise

Detector Technology

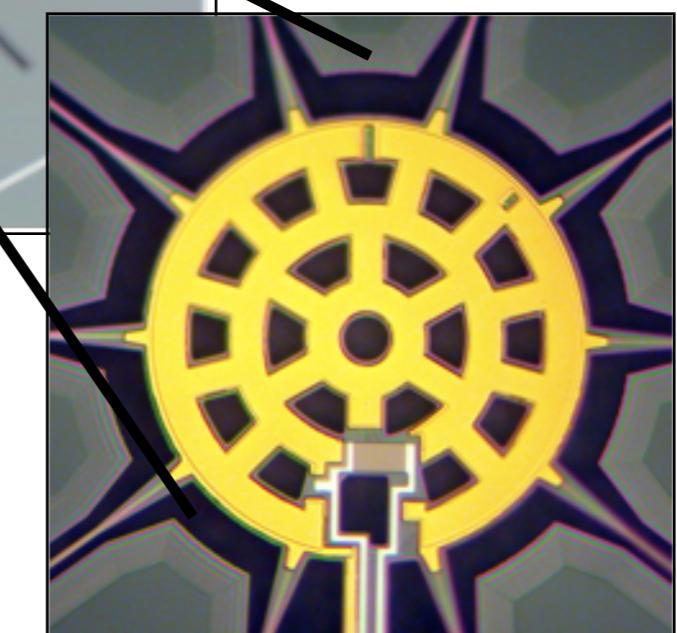
SPT focal plane
(cooled to 0.3 degrees
above absolute zero)



each detector is a
3mm diameter web that
absorbs microwaves and heats up



At the center is a
transition edge
sensor (TES)
thermistor $\sim 25 \text{ }\mu\text{m}$

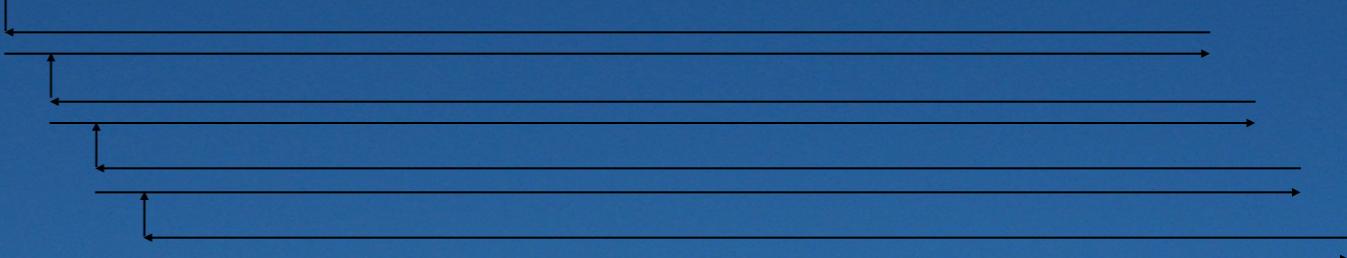


Wedge of
160 detectors,
960 detectors total,
 ~ 800 working

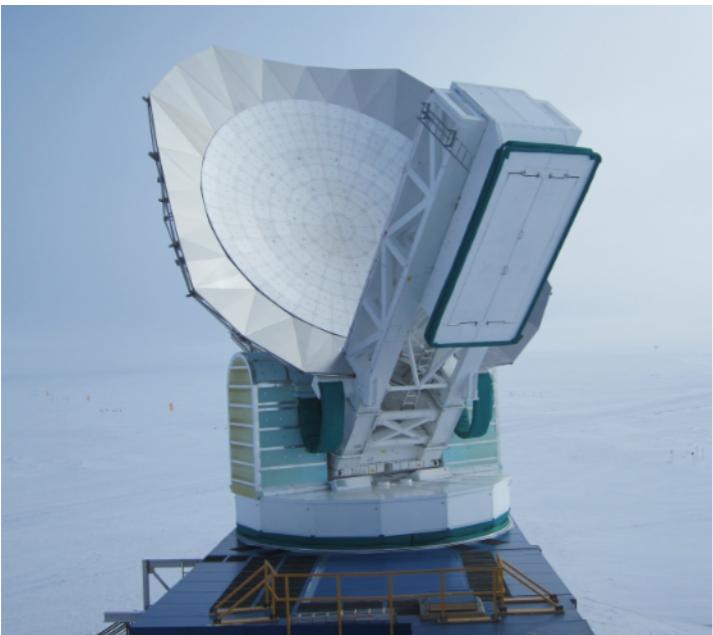
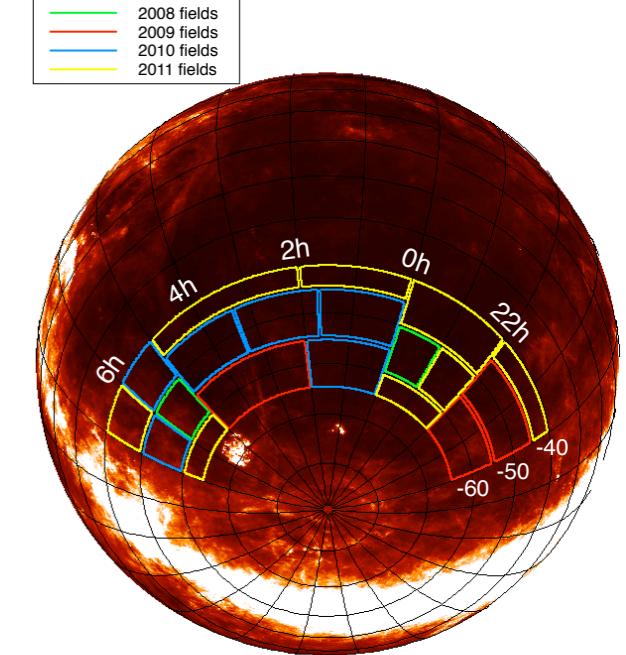
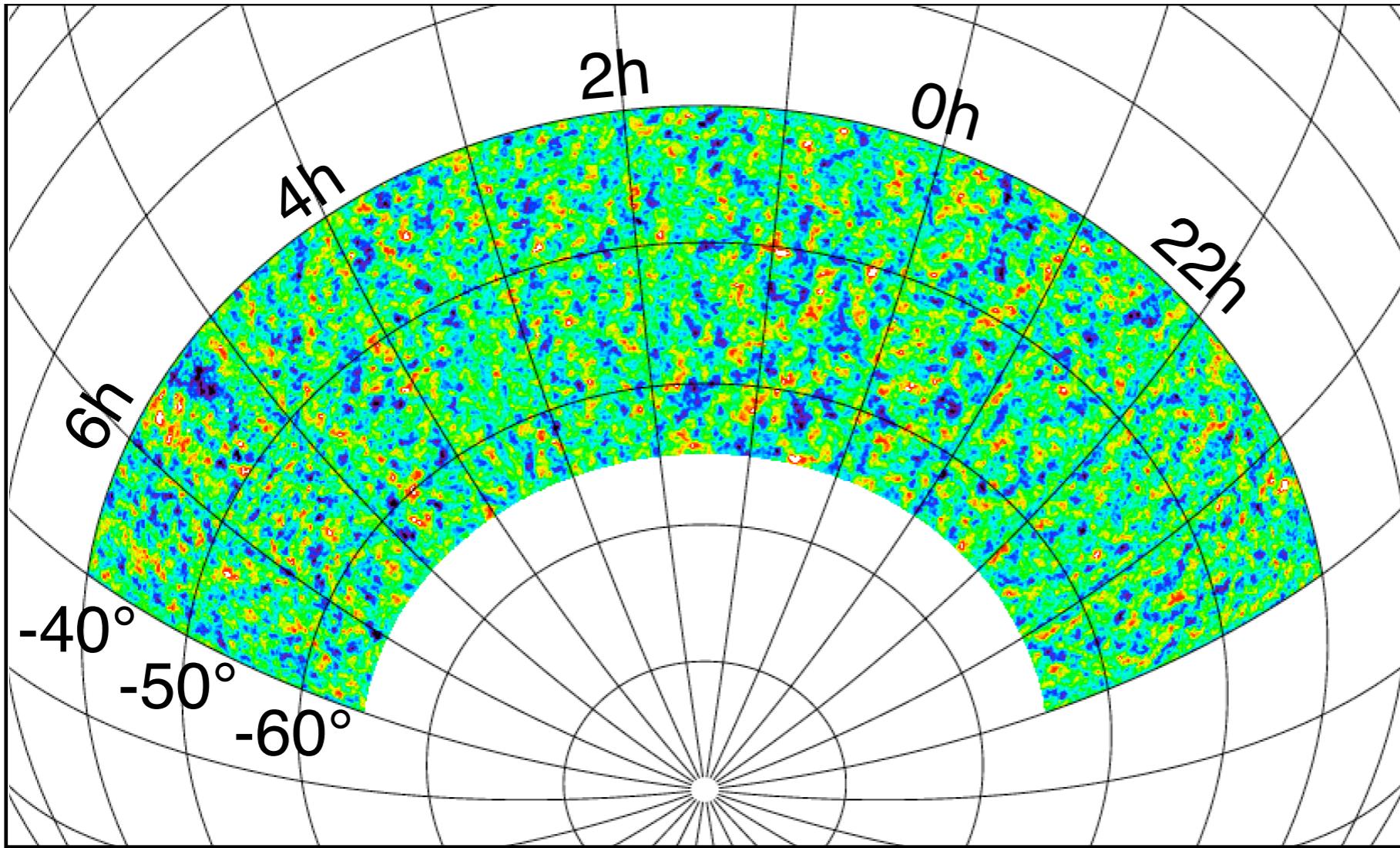
Problem: low frequency 1/f noise from the instrument and atmospheric fluctuations contaminate the astrophysical signal.

Solution: fast scanning – noise at low *temporal* frequencies contaminates only low *spatial* frequencies in the data

...continue to top of field, then repeat



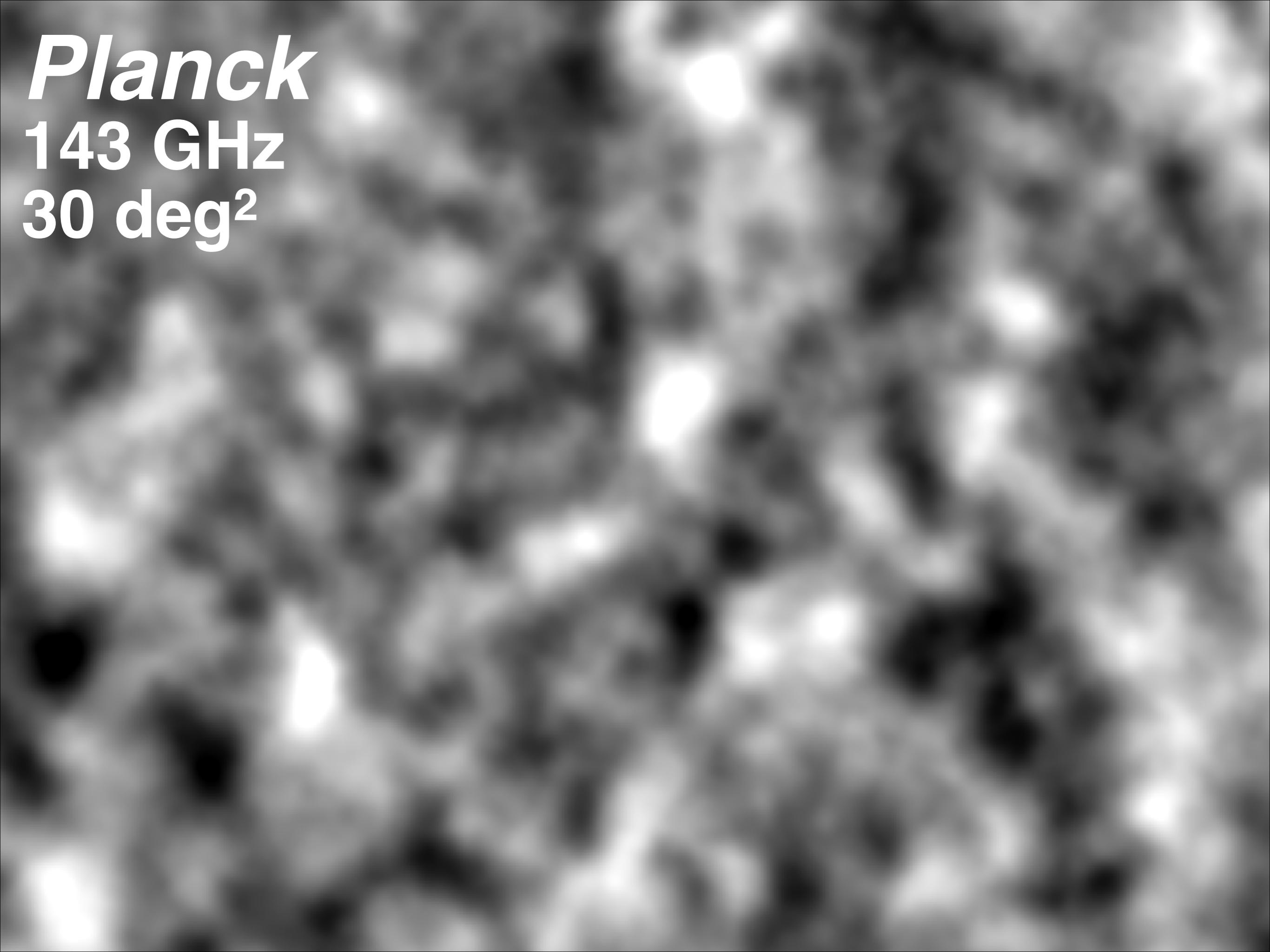
2500 deg² SPT-SZ Survey

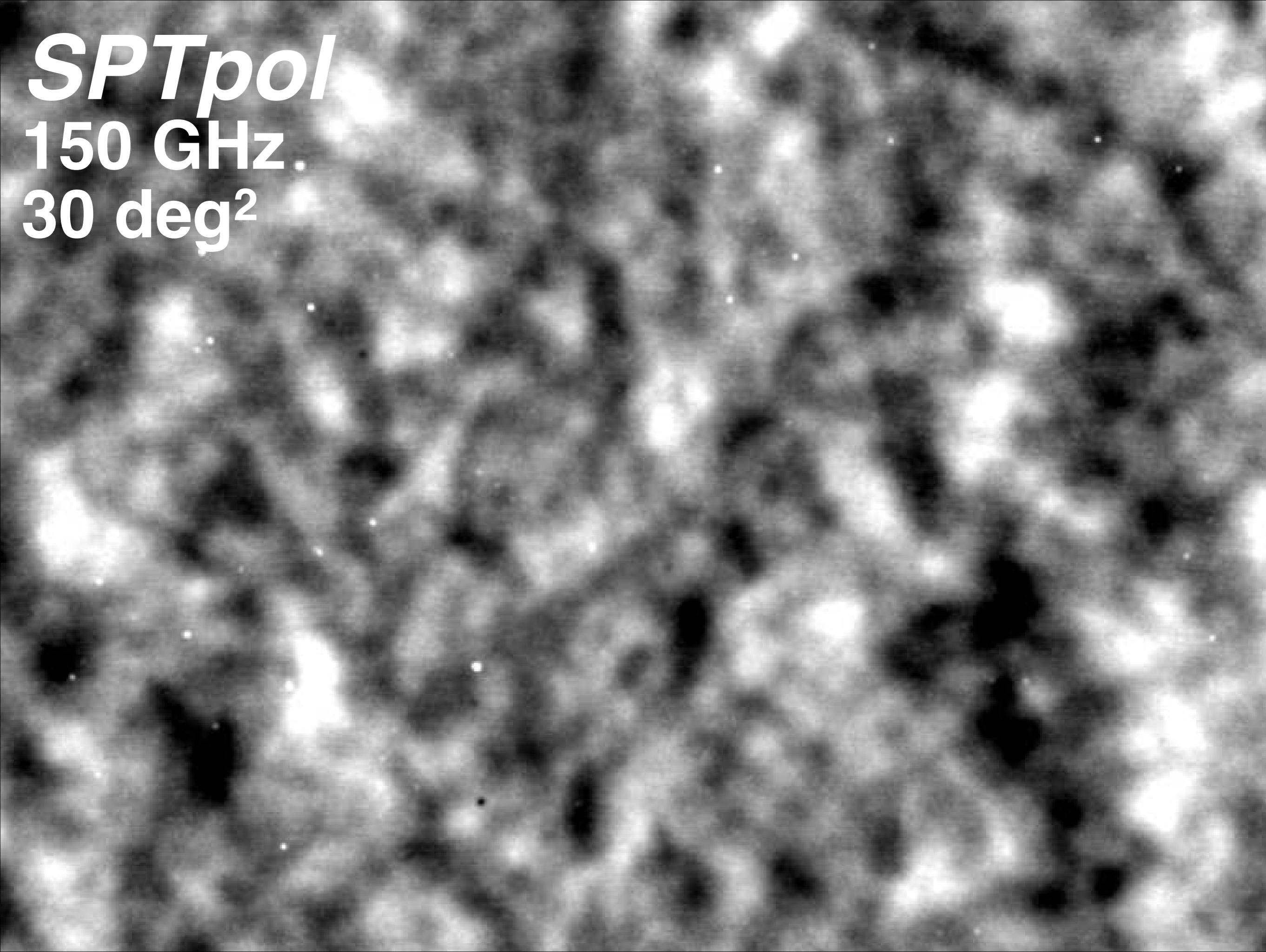


		SPT-SZ	2008 → 2011	Deep Field	2008 → 2011	SPTpol	2012 → 2014	SPT3G	2015 → 2017
band [mm]	FWHM [']	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam	uK-arcmin	RMS mJy/beam
3	1.7	42	2	42	2	6.5	0.3	4.2	0.2
2	1.2	18	1.3	13	0.9	4.5	0.3	2.5	0.2
1.4	1	85	6.8	35	3	--	--	4	0.4
area [deg ²]		2500		200		600		2500	

WMAP
W-band
30 deg²

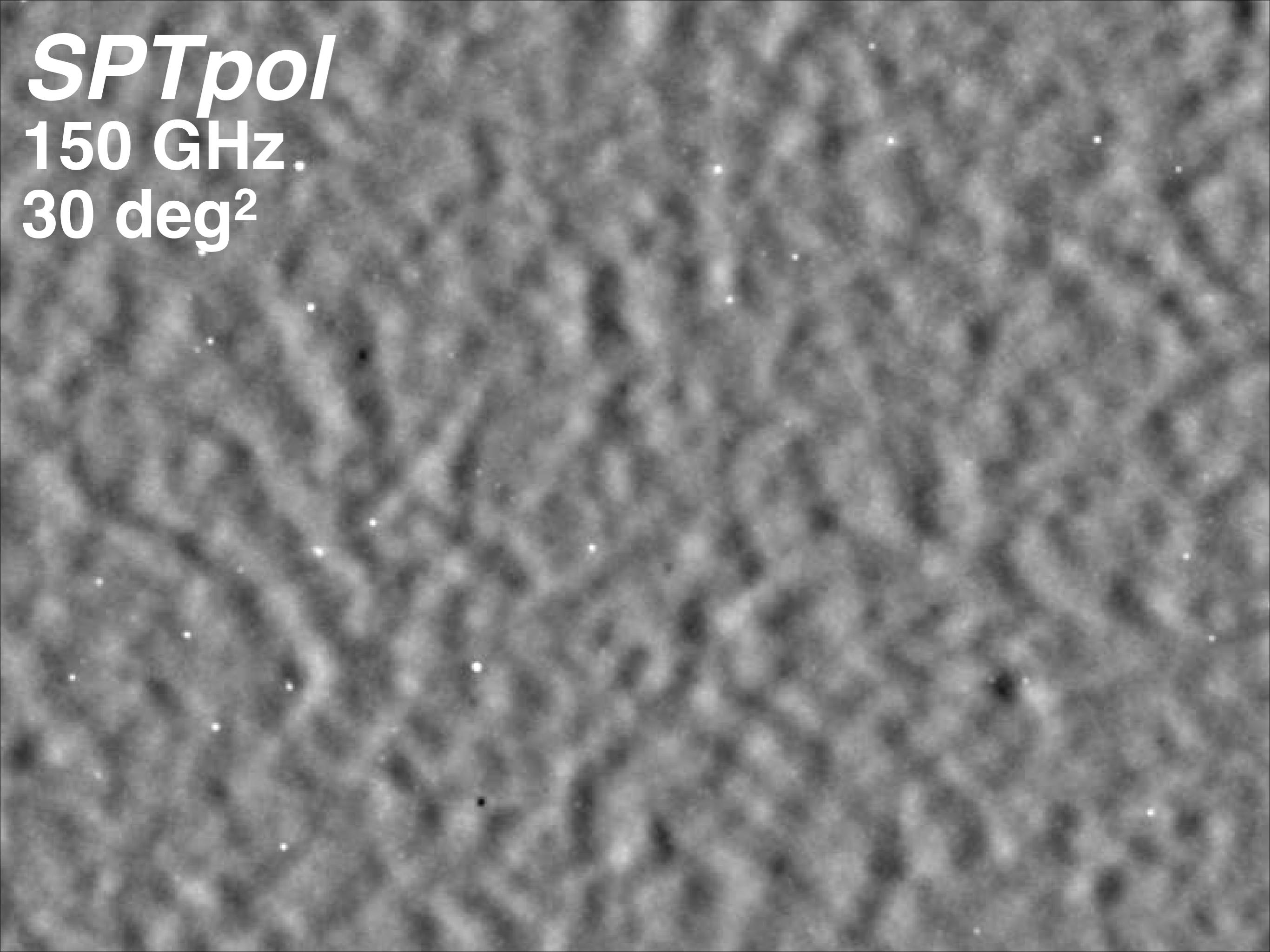
Planck
143 GHz
30 deg²

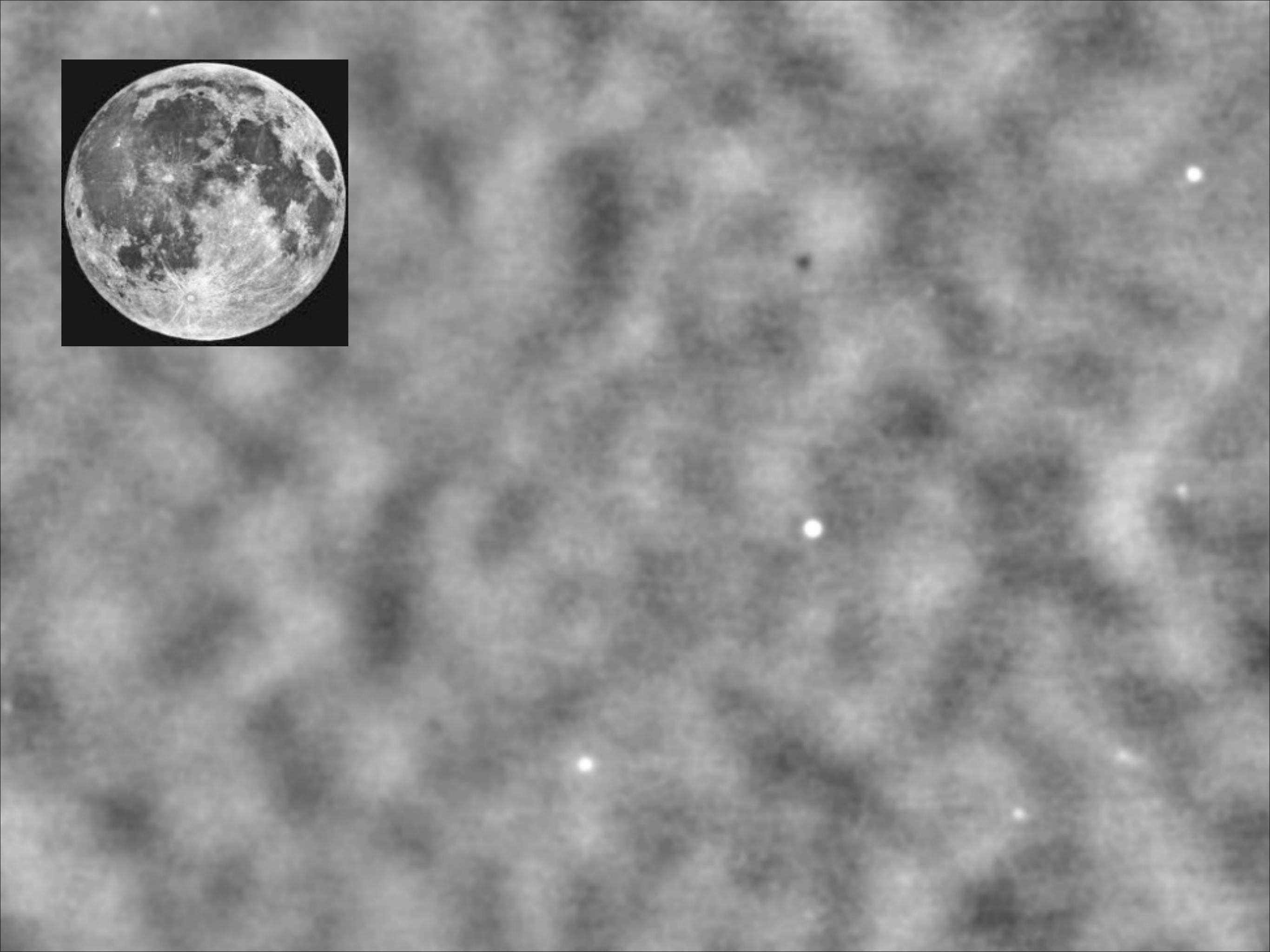




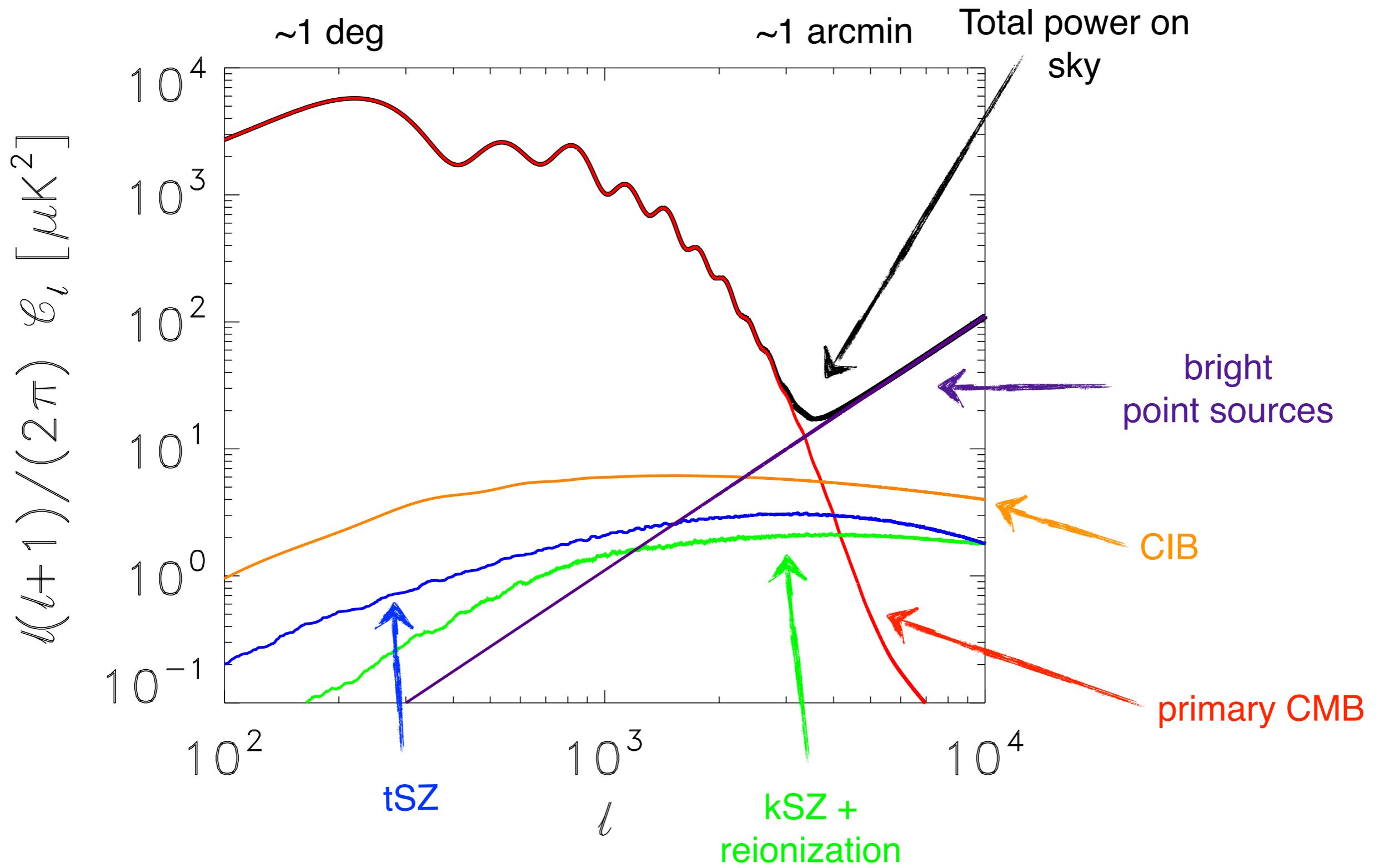
SPTpol
150 GHz.
30 deg²

SPTpol
150 GHz.
30 deg²

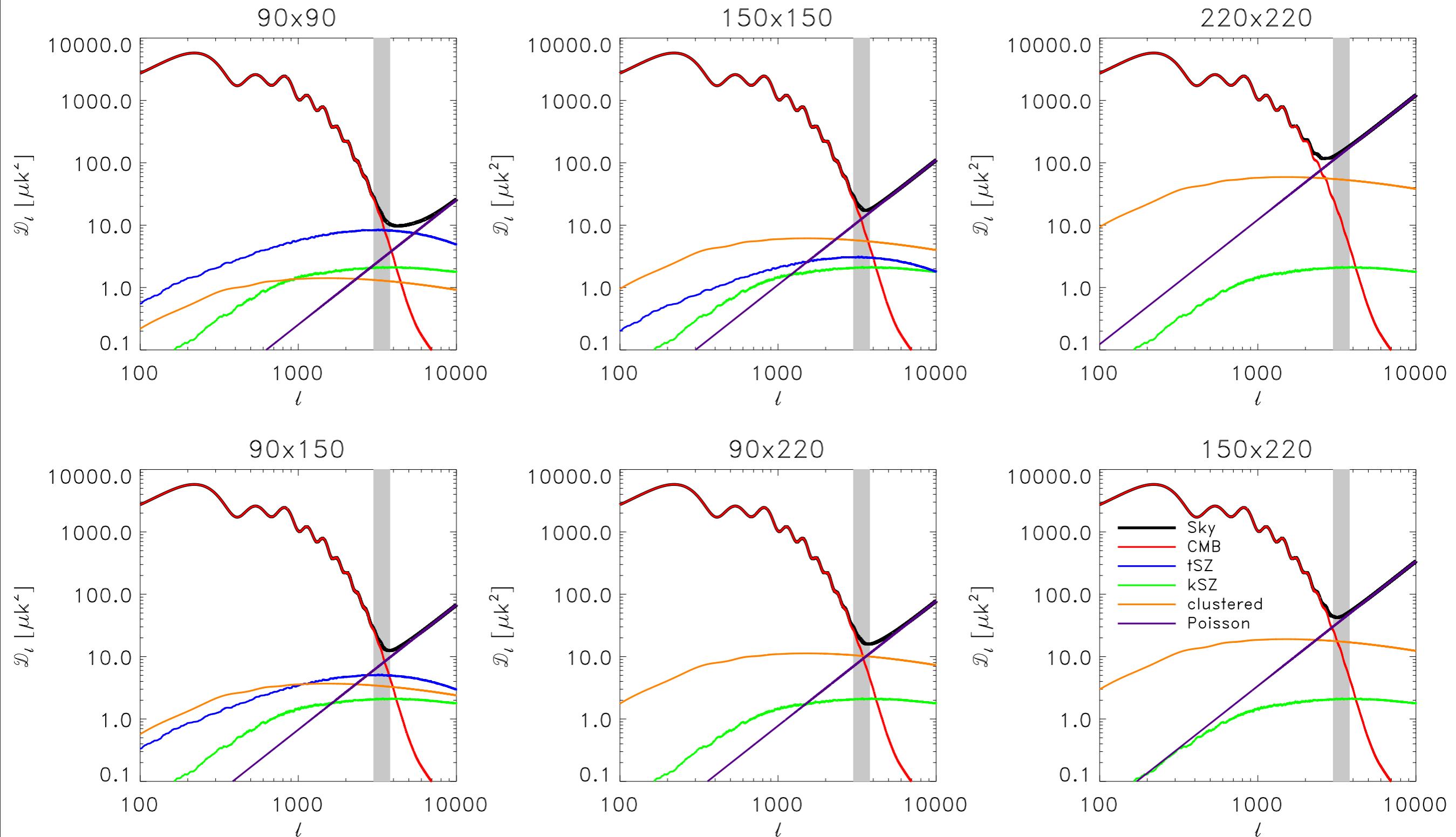




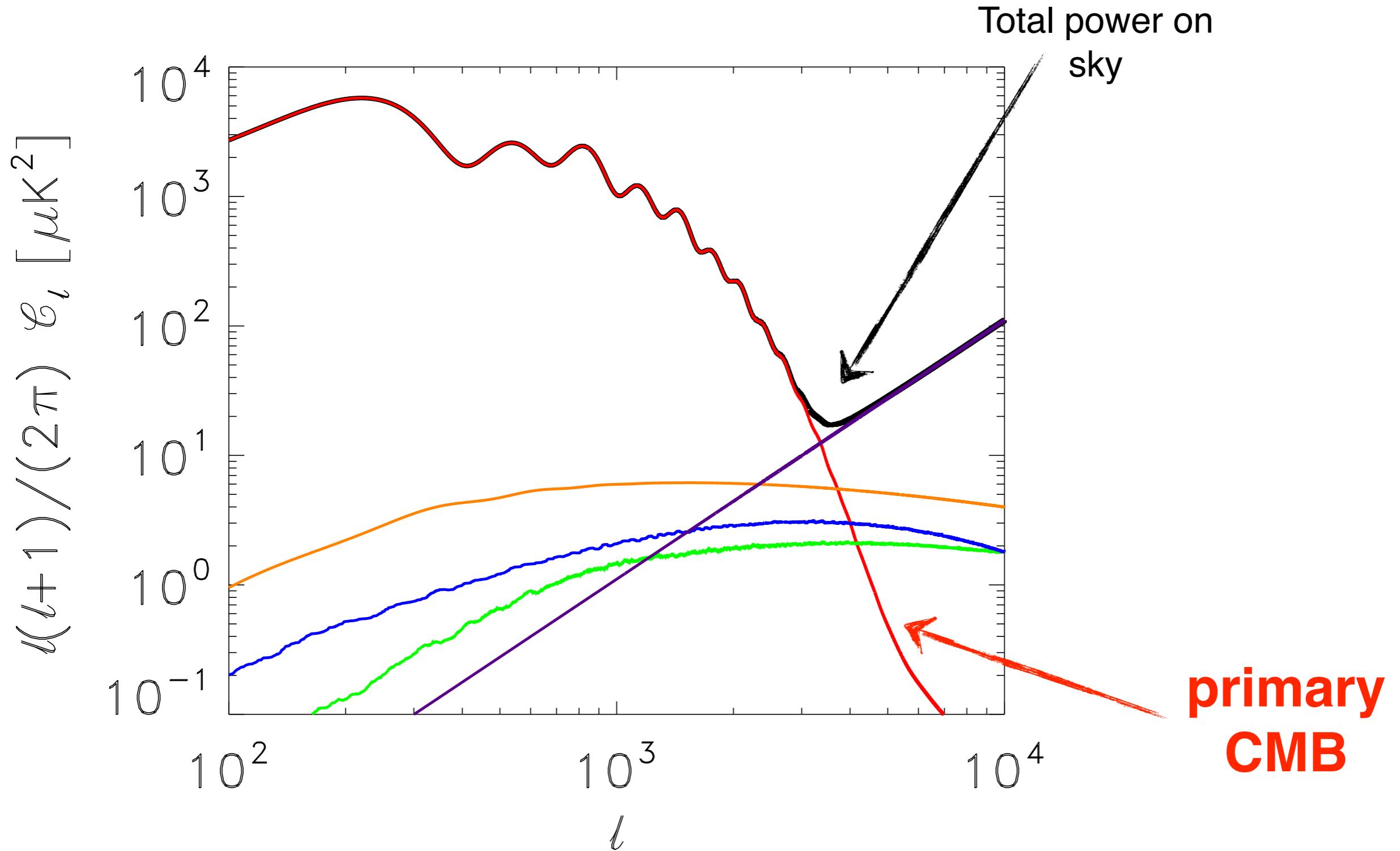
Fluctuations in the mm Sky



Power Spectrum Components

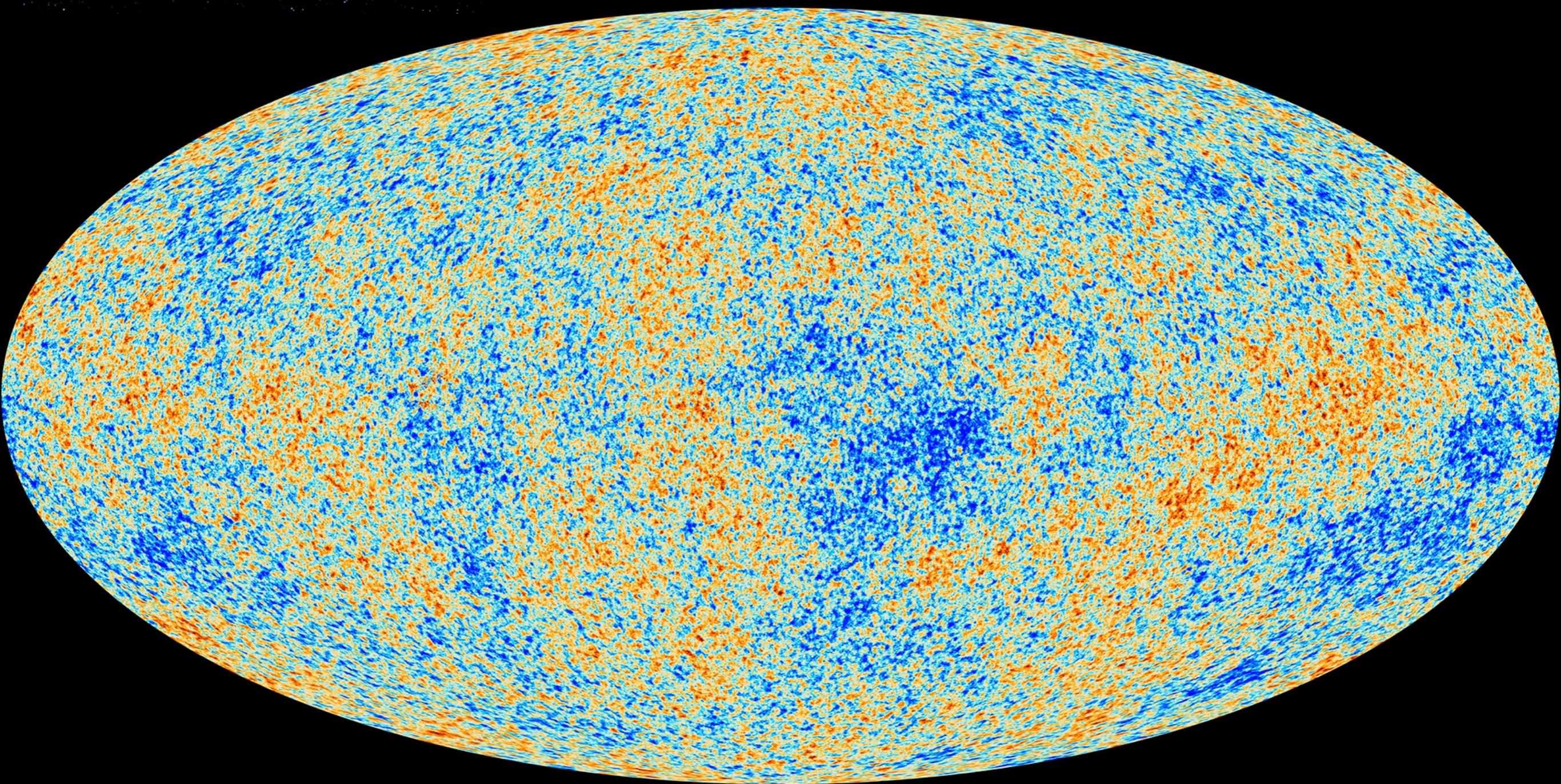


CMB

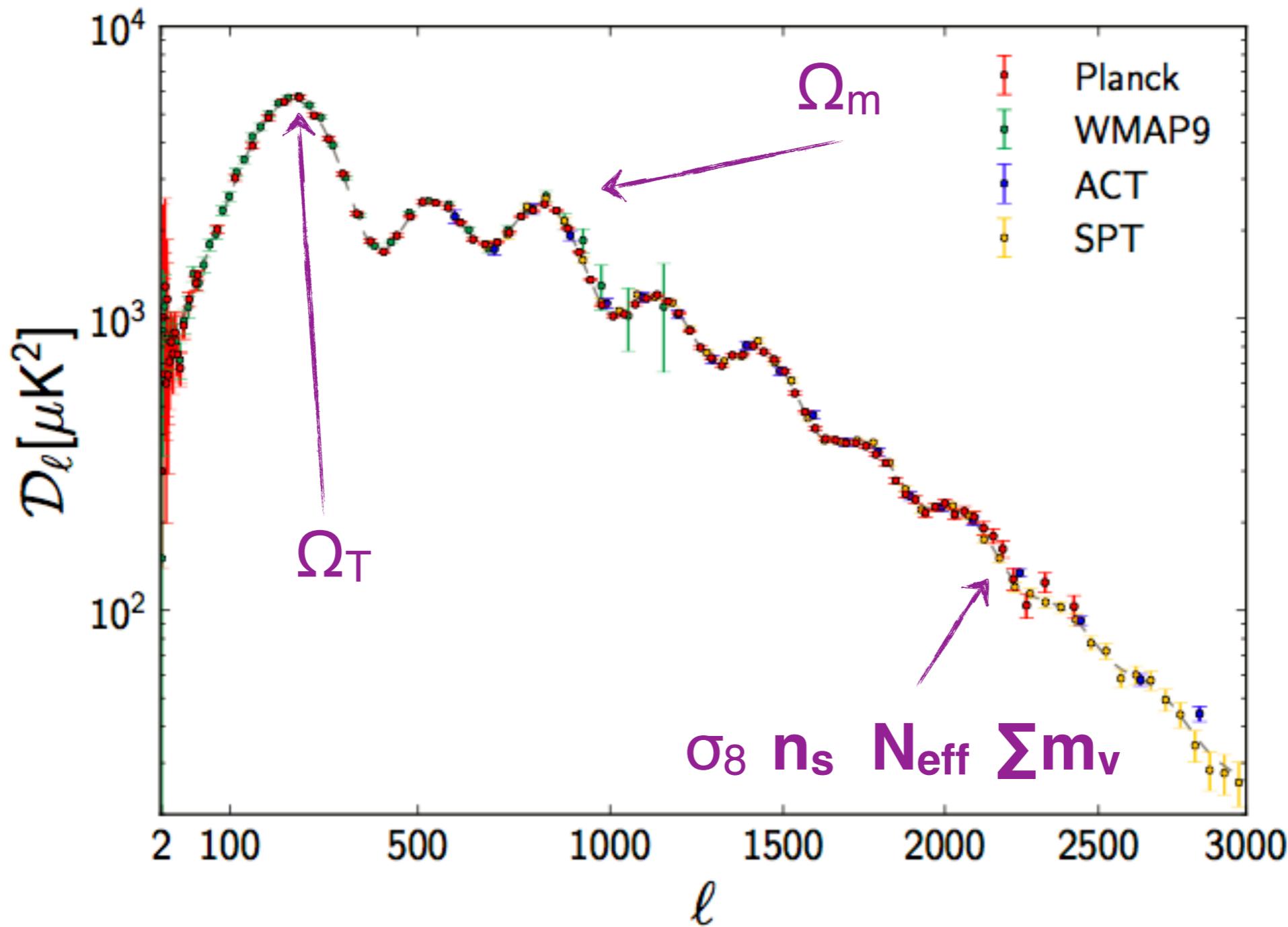




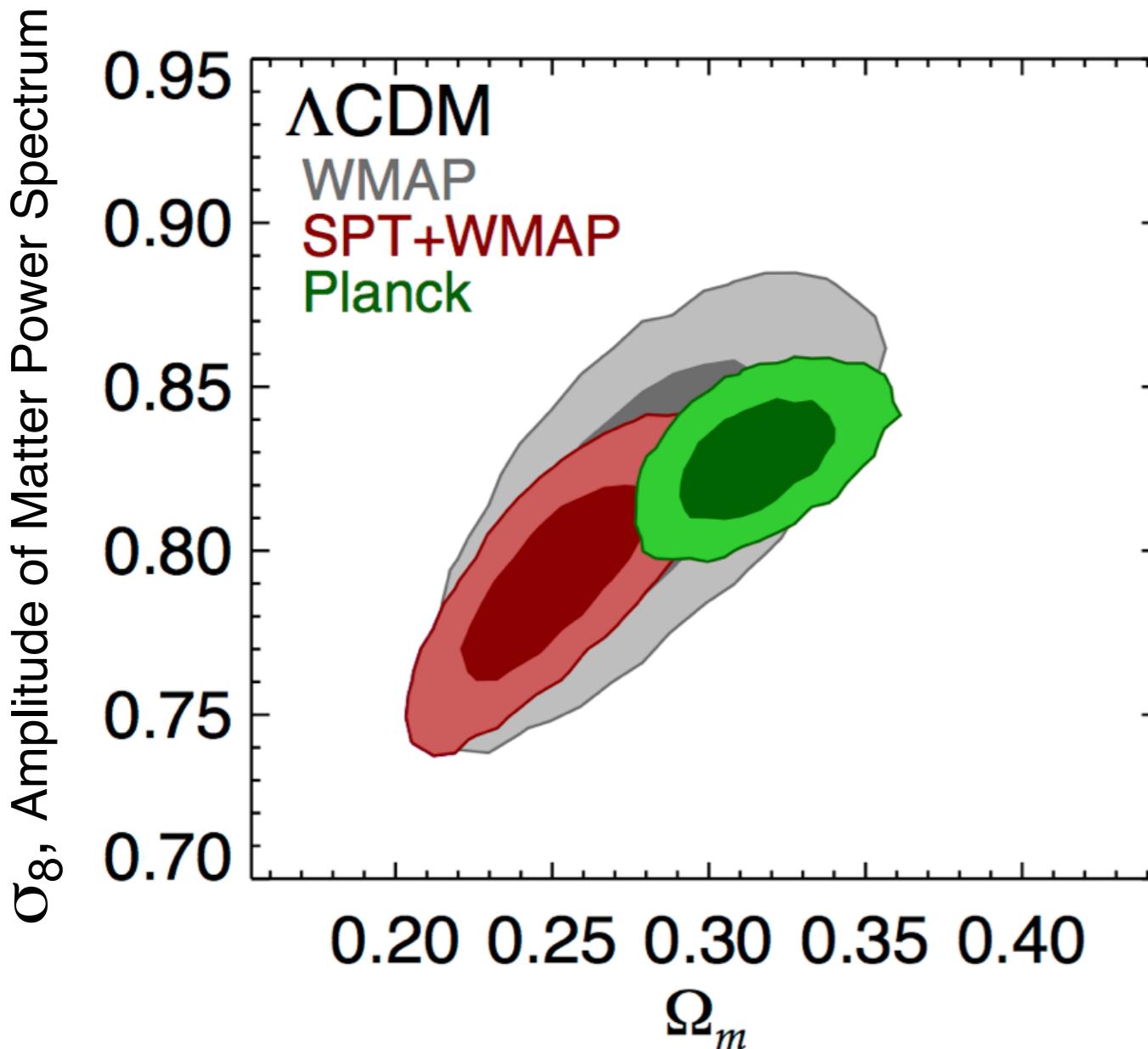
ESA Planck Satellite



Primary CMB anisotropy



CMB Constraints on σ_8, Ω_m



Planck measurements favor a shift in σ_8 and Ω_m
Driven by:

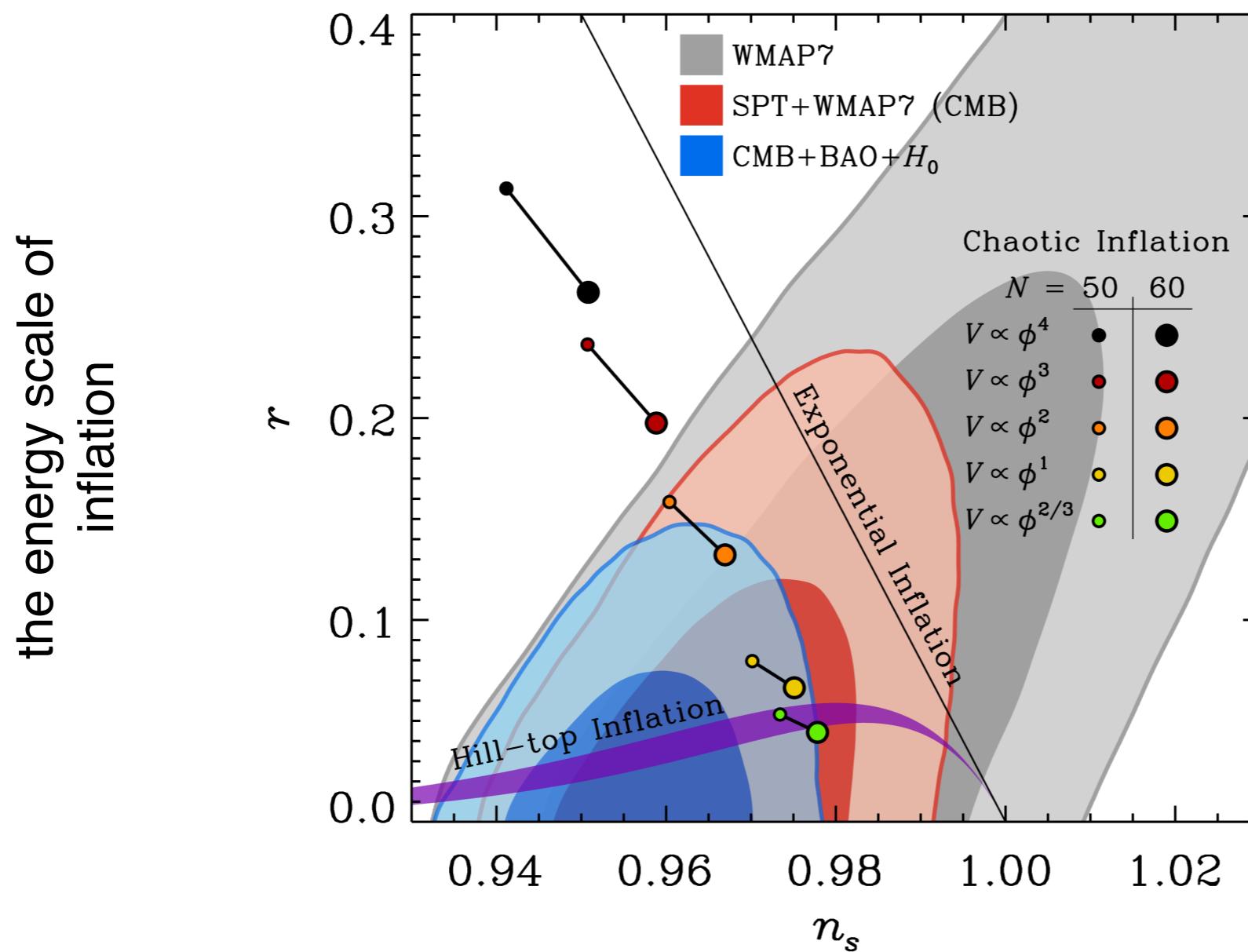
- 1st/3rd acoustic peak power ratio
- Gravitational lensing in the CMB power spectrum (Ω_m goes down by $\sim 1\sigma$ when A_{Lens} is free)

	WMAP7	WMAP7+SPT	Planck-CMB
σ_8	$0.819 +/ - 0.031$	$0.795 +/ - 0.022$	$0.829 +/ - 0.012$
Ω_m	$0.276 +/ - 0.029$	$0.250 +/ - 0.020$	$0.315 +/ - 0.016$

(WMAP7) Komatsu
+2011

(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

Constraints on Inflation



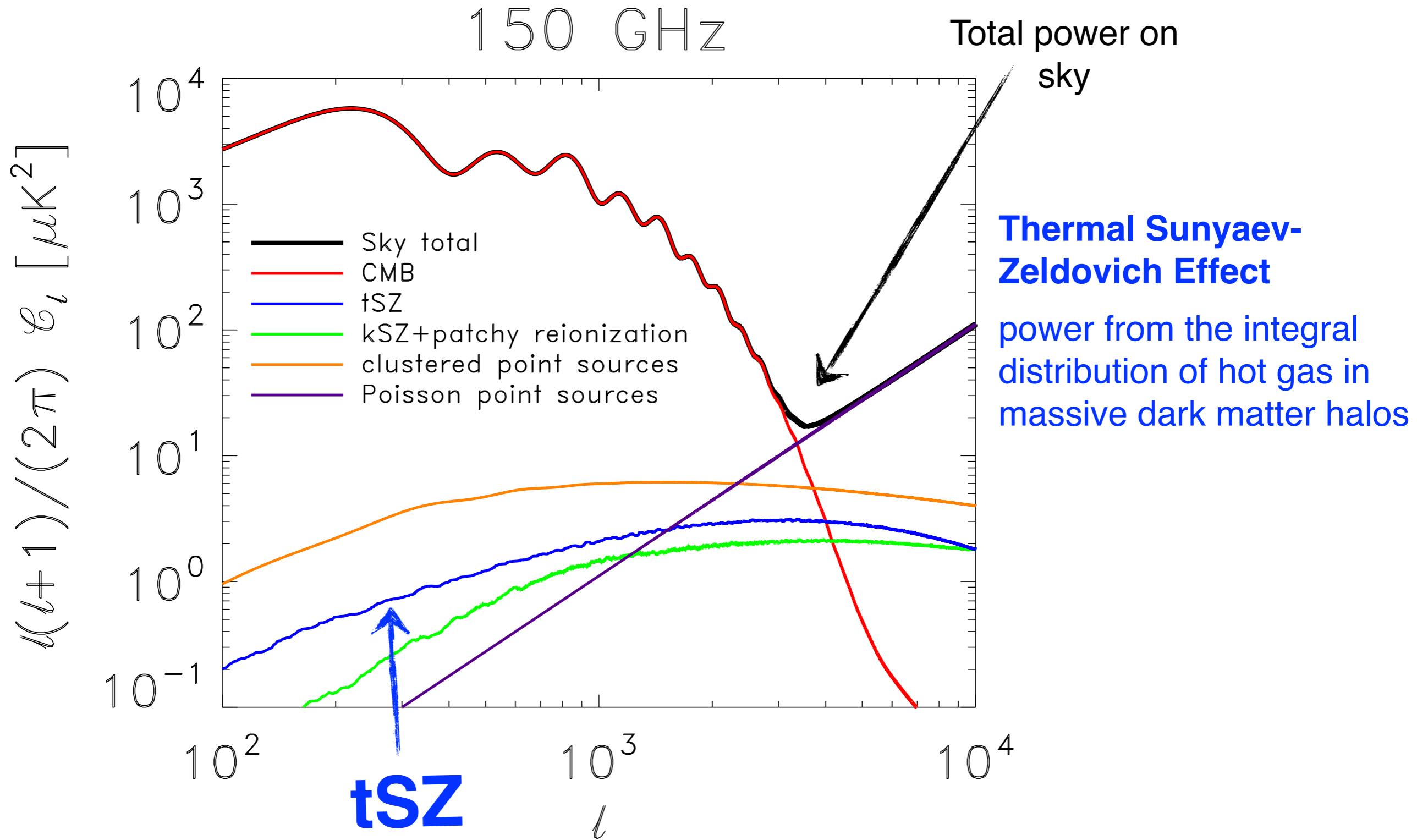
slope of the CMB damping tale
inflation predicts $n_s \neq 1$

$$\Delta_R^2(k) = \Delta_R^2(k_0) \left(\frac{k}{k_0} \right)^{n_s - 1}$$

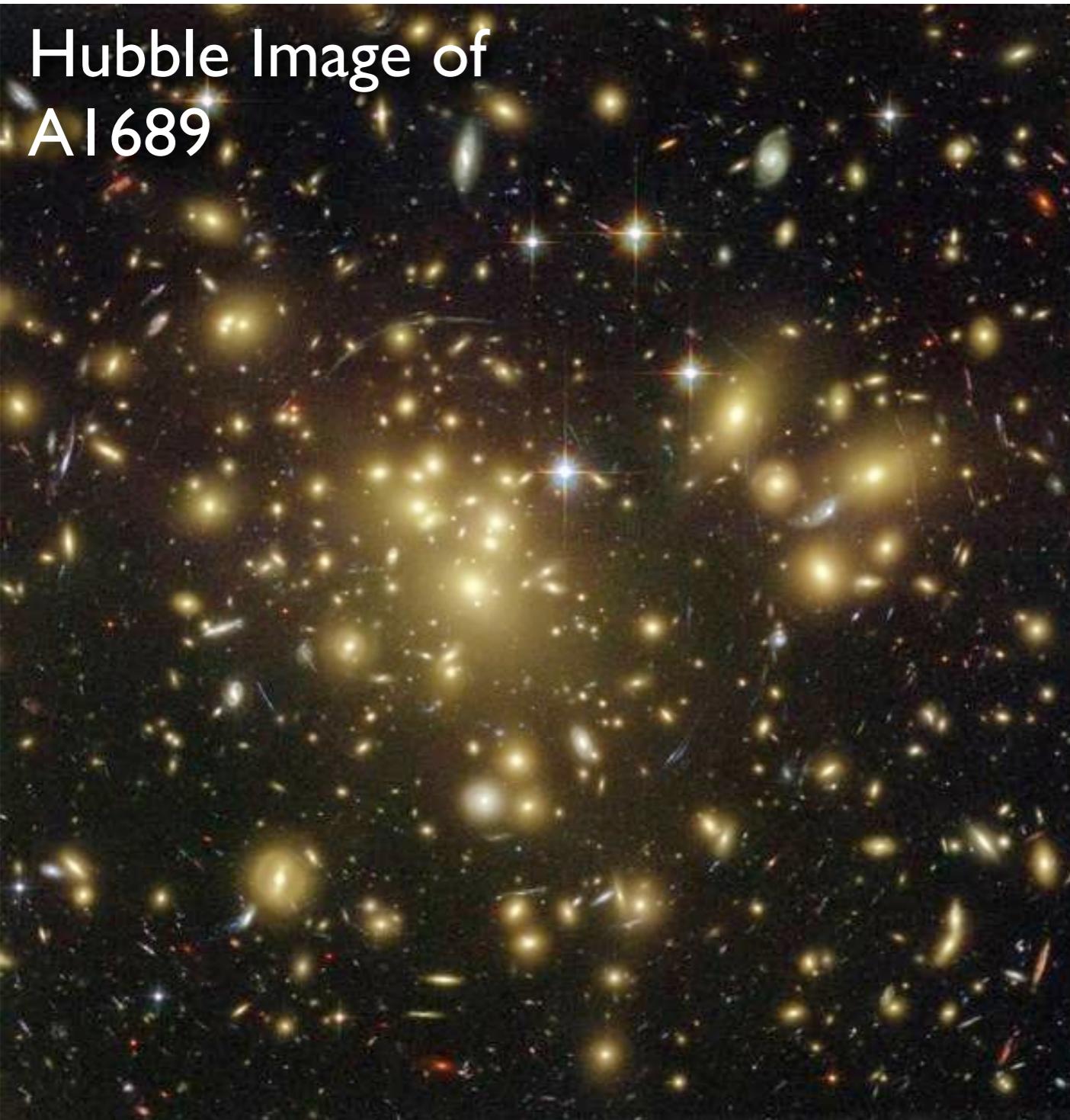
$$r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

(tensor/scalar) ratio

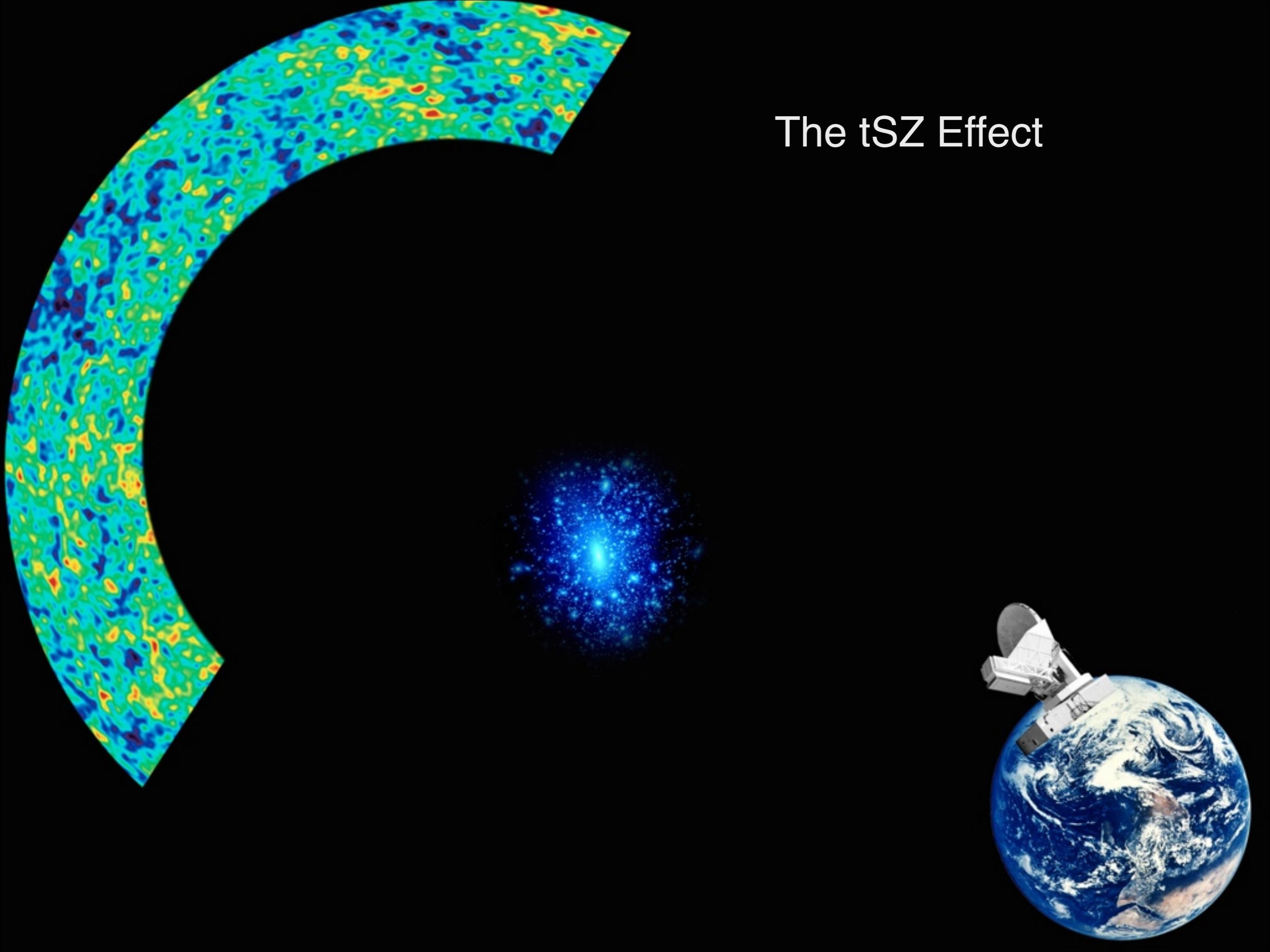
Sunyaev-Zeldovich Effect



Clusters of Galaxies



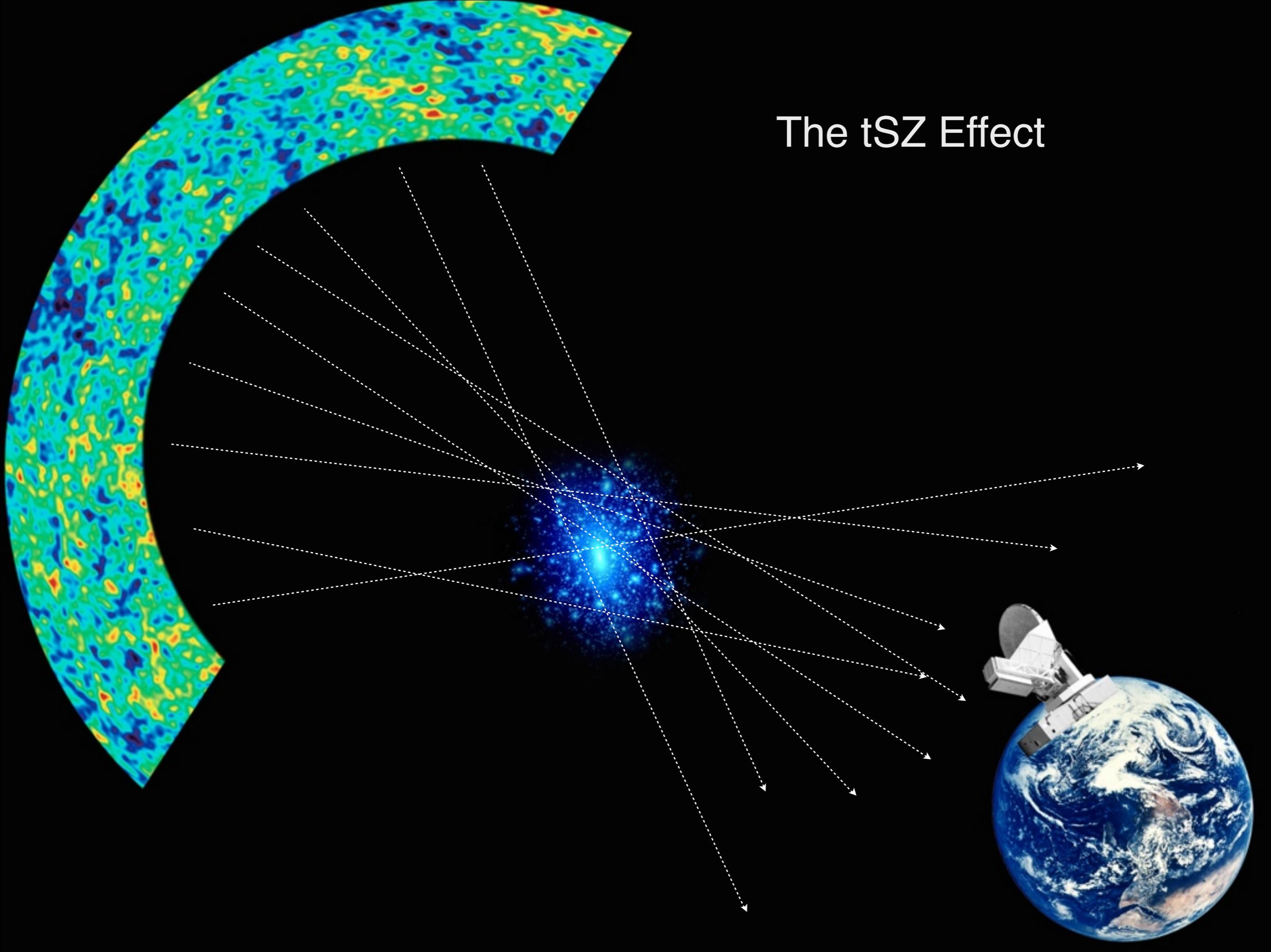
- They are the most massive, rare objects in the Universe - **the number abundance of massive clusters is very sensitive to cosmology**
- The biggest clusters contain thousands of galaxies
- Take billions of years to form



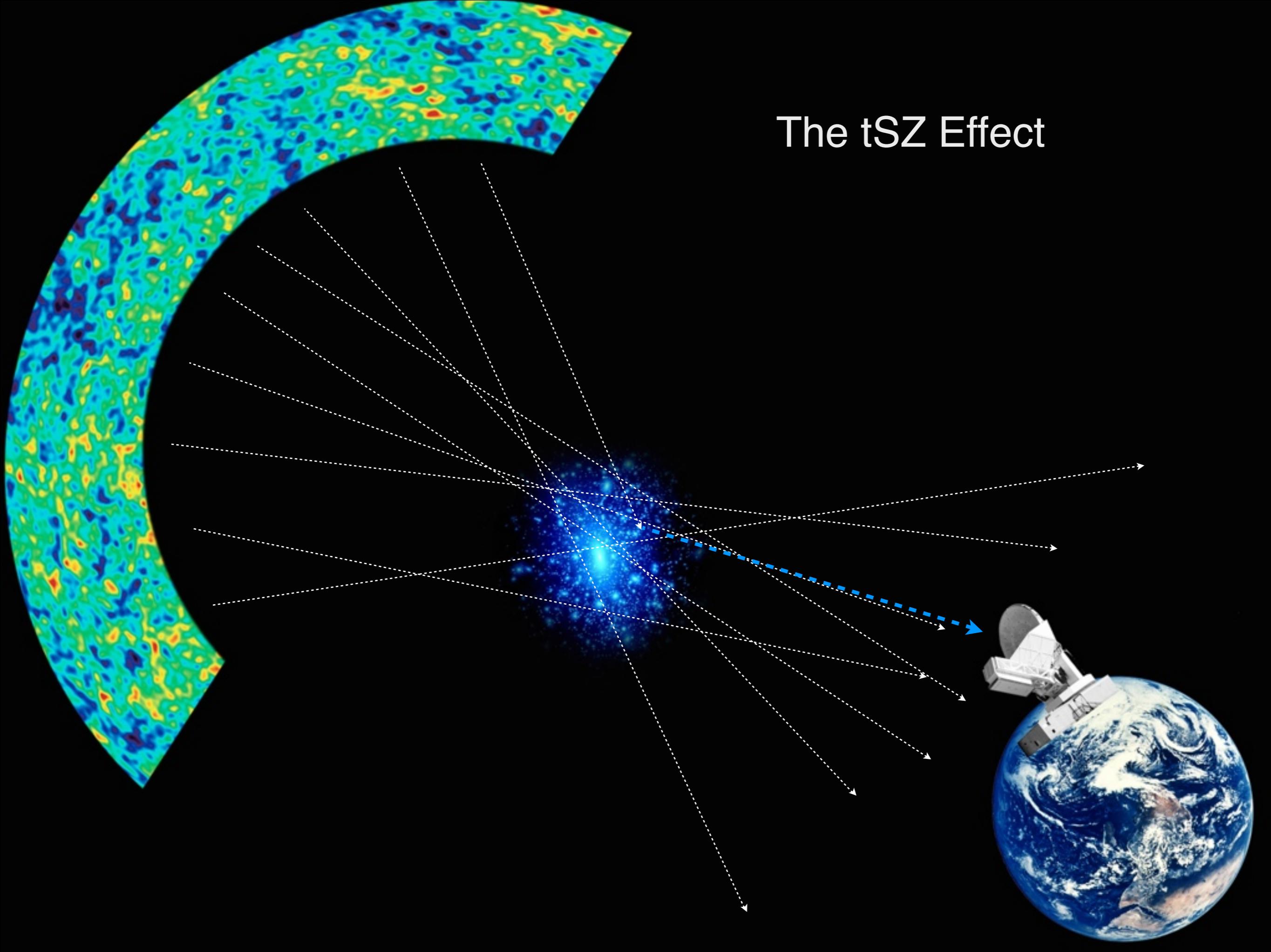
The tSZ Effect



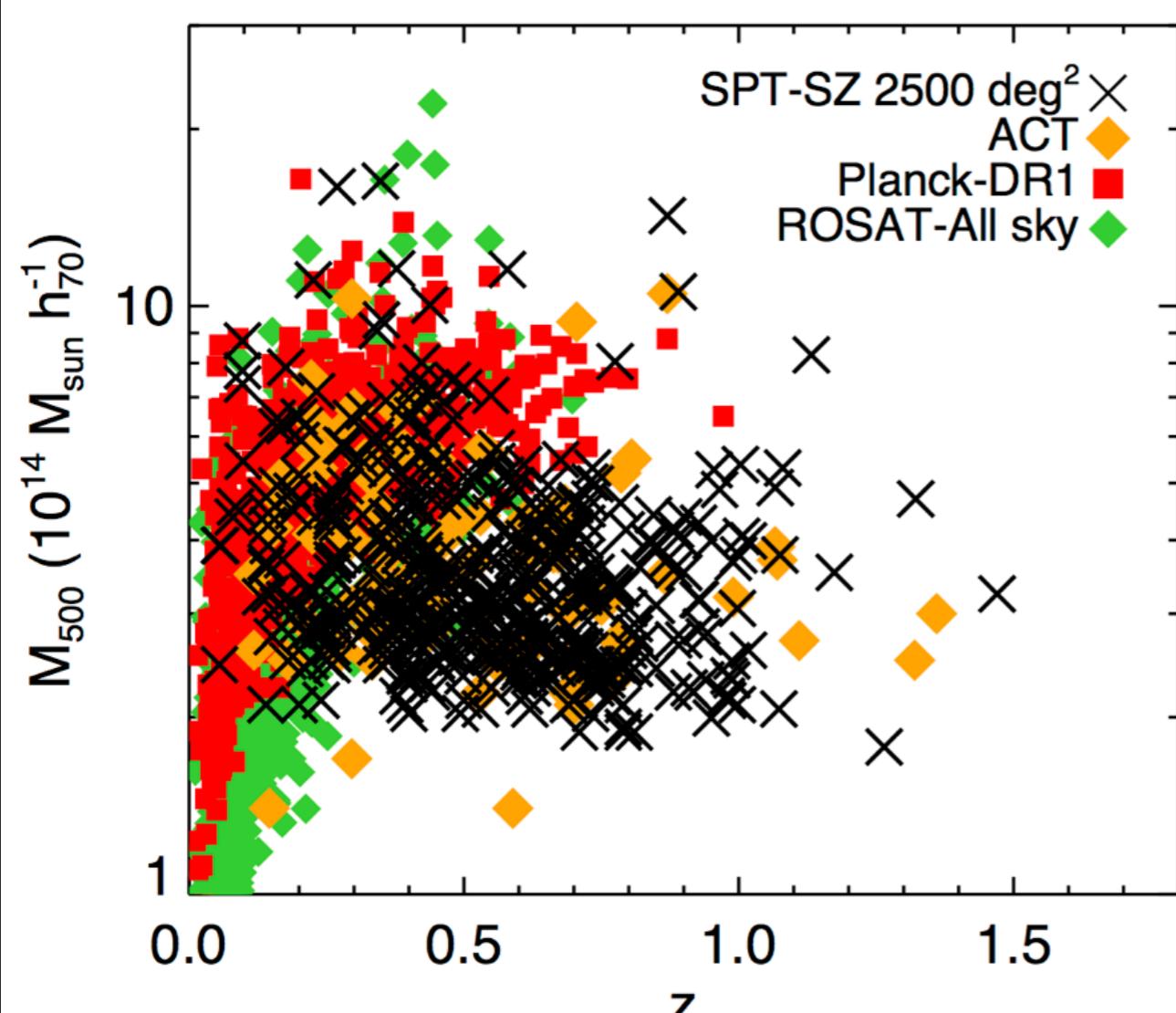
The tSZ Effect



The tSZ Effect



SZ Cluster Surveys: *Mass vs Redshift*



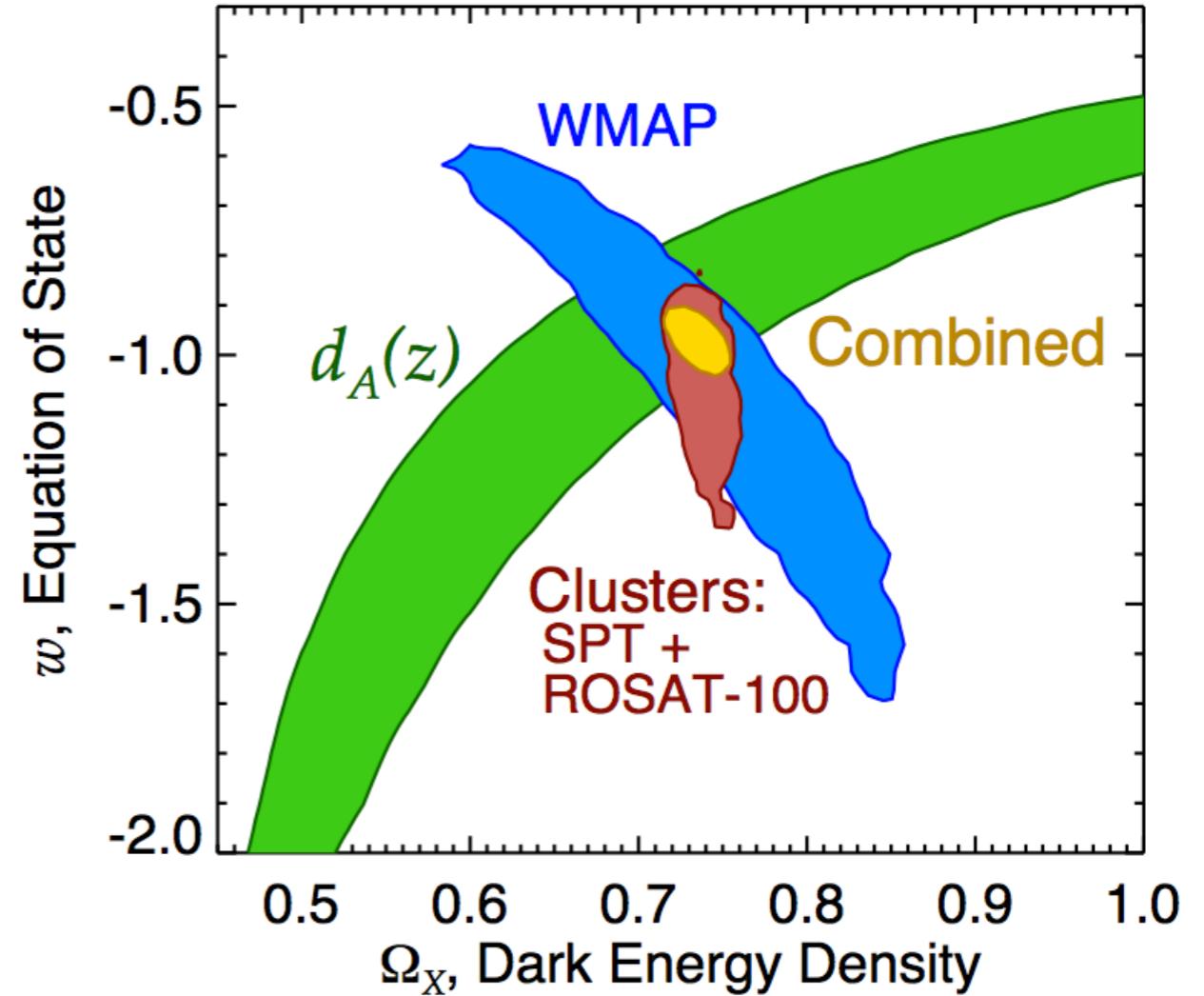
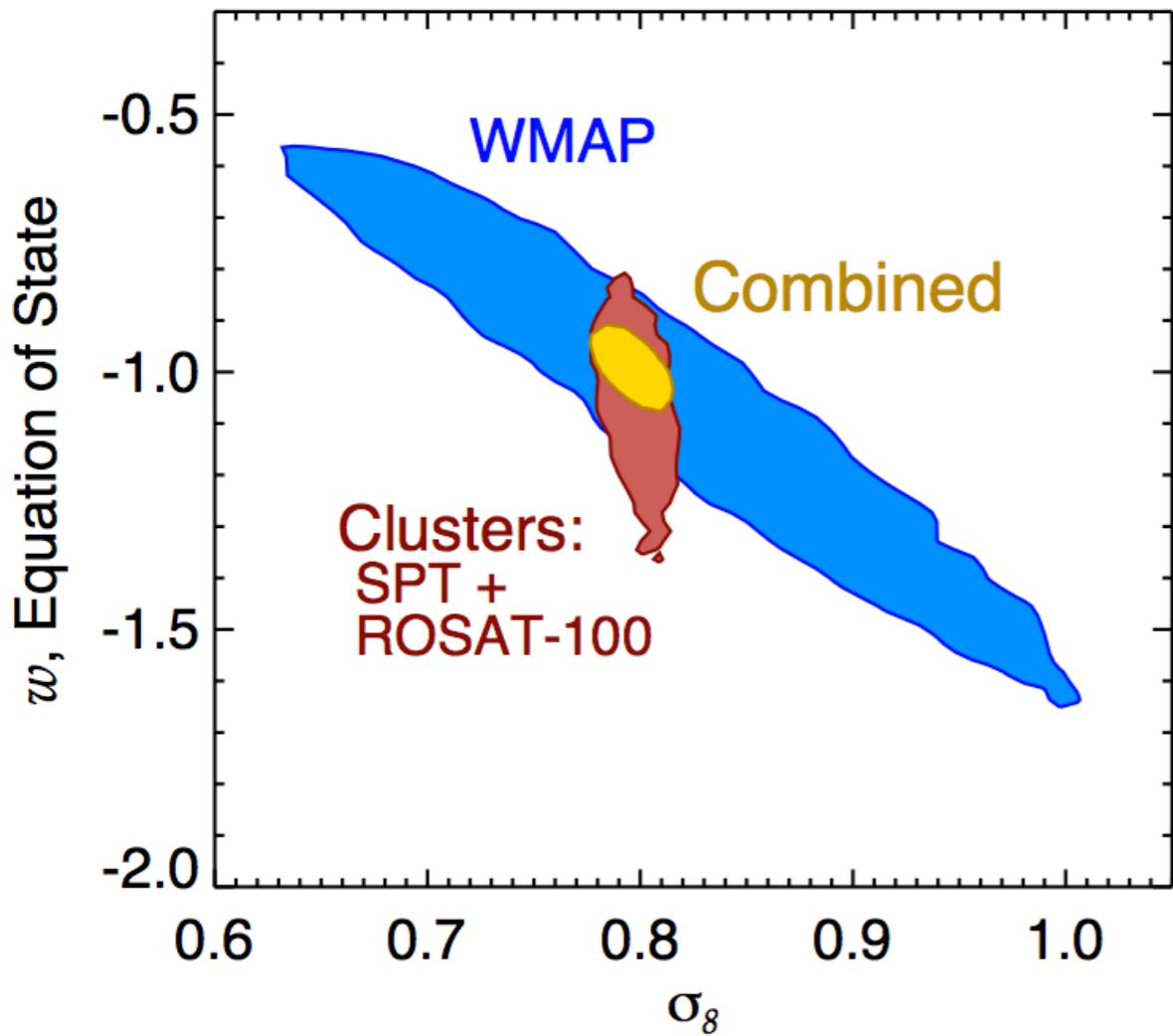
First SZ-discovered cluster was
in 2008 by SPT (Staniszewski
et al 2009);
5 years later there are
> 1300 SZ-identified clusters!

	Area (deg ²)	Depth (uK-arcmin)	N _{clusters}
Planck	All-sky	45	861
SPT	2500	17	465
ACT	950	23-40	91

Notes:

- For each experiment, the 150 GHz depth is given, most important band for cluster counts
- Planck based on ~1/2 survey, cluster counts should ~double for full survey
- N_{clusters} highly dependent on completeness of optical follow-up, which varies between each experiment

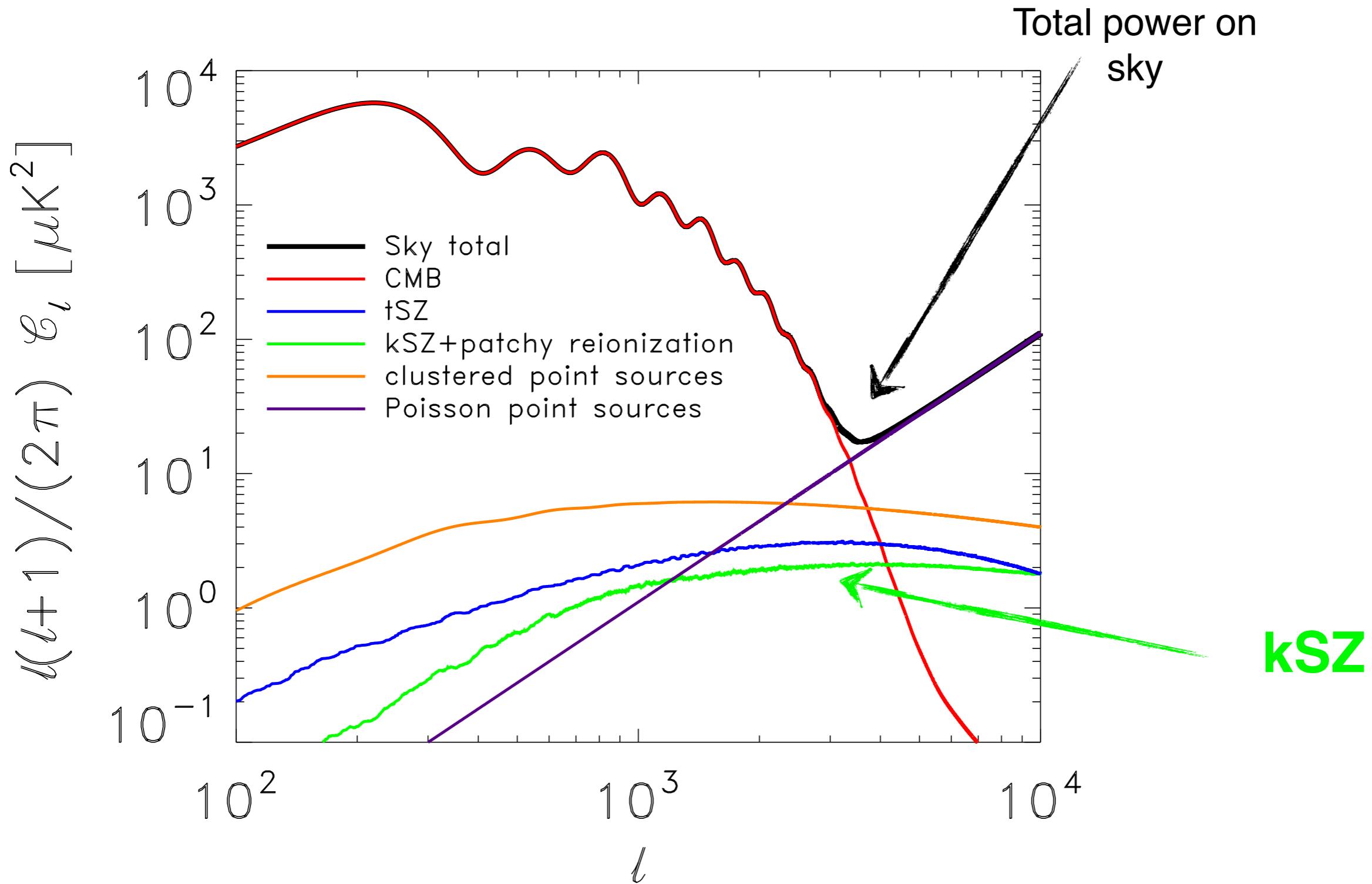
anticipated SZ cluster cosmology constraints



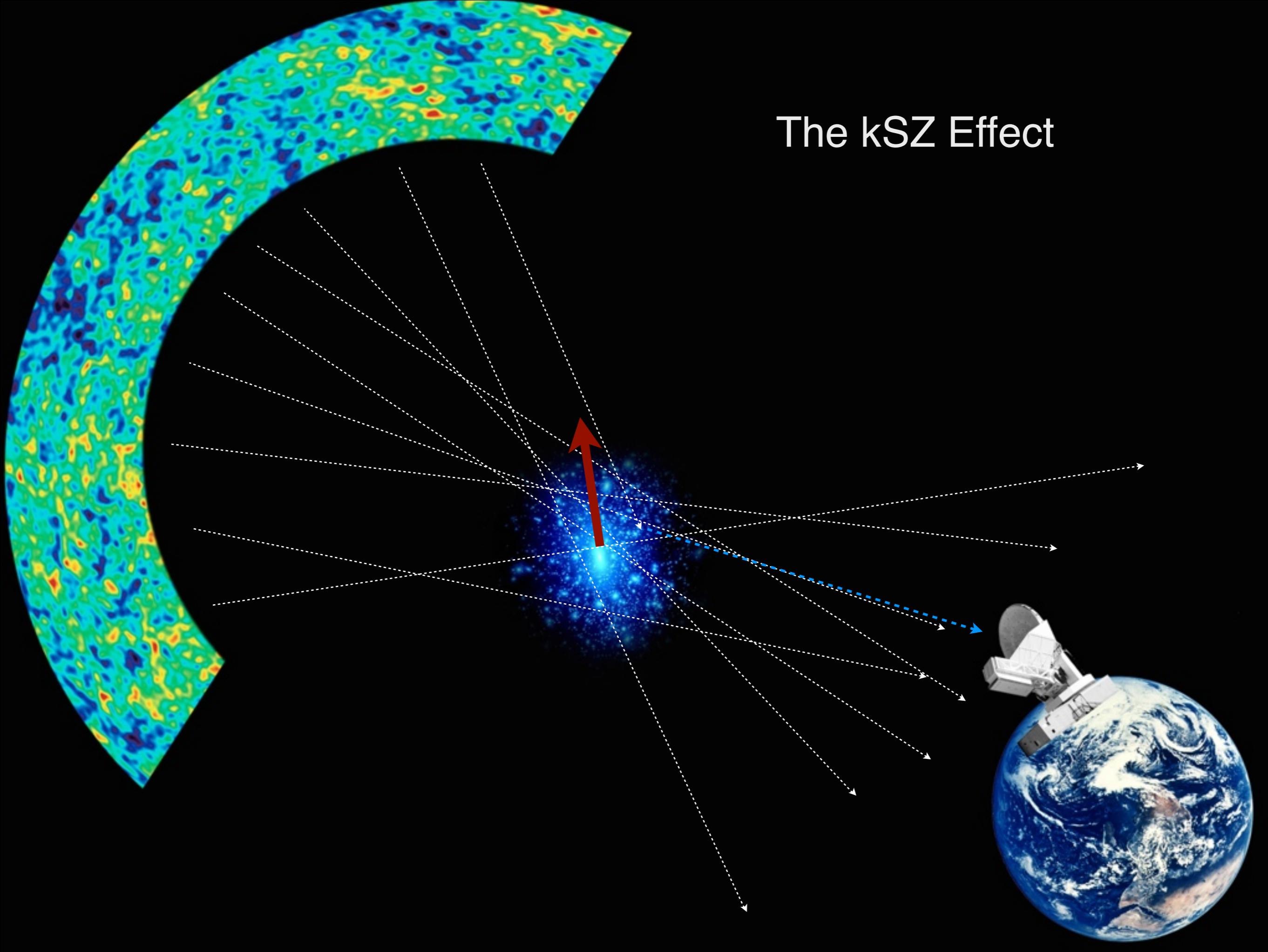
SPT 2500 deg² survey of ~450 clusters at S/N > 5
X-ray based mass calibration with 5% mean from 80 clusters
⇒ constrain σ_8 to $\pm 1.2\%$; w at $\pm 4.6\%$

*Independent of geometric cosmological constraints (SN, BAO).
Note 3.3% systematic uncertainty in w from mass calibration.*

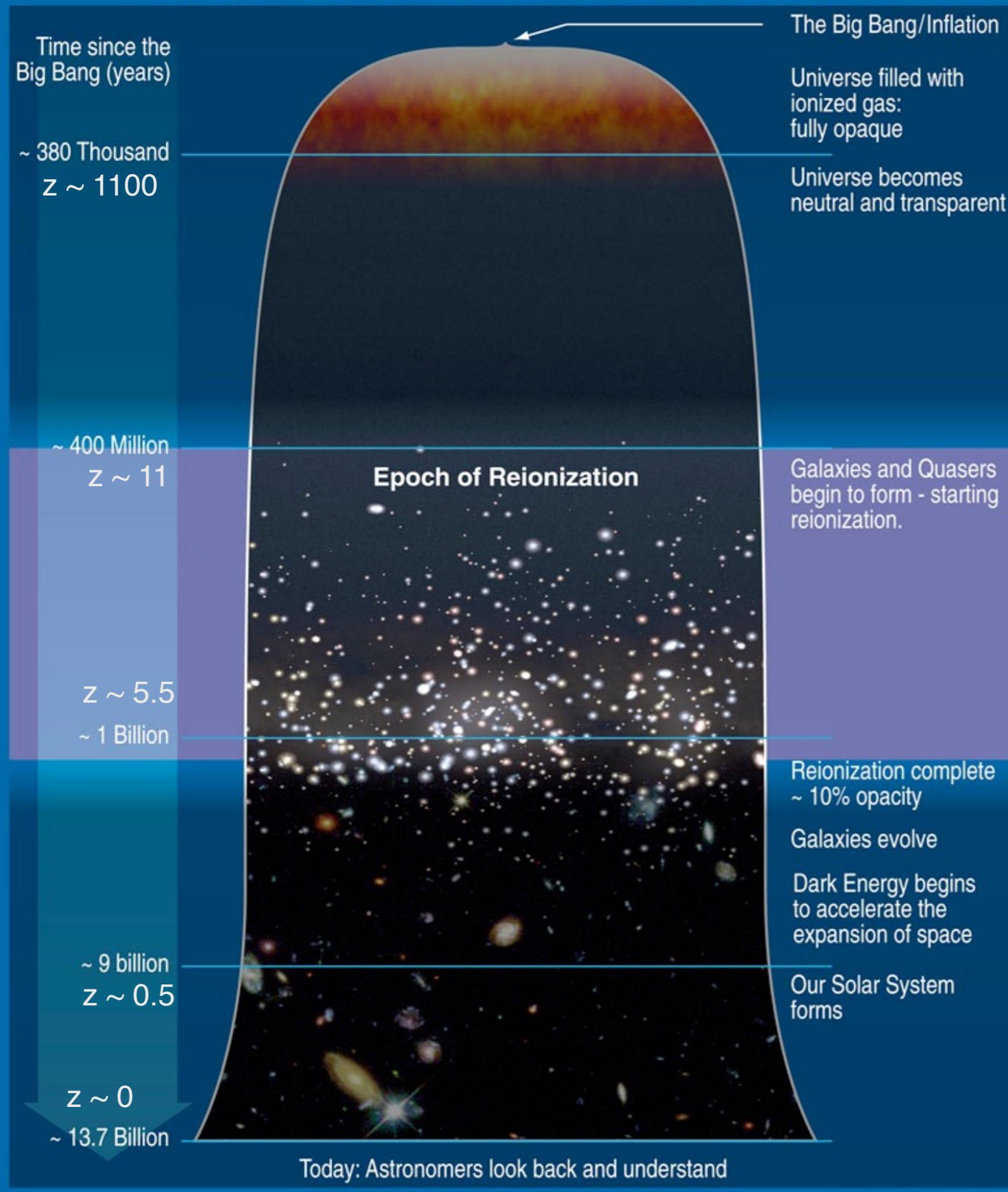
Epoch of Reionization



The kSZ Effect



First Stars and Reionization Era

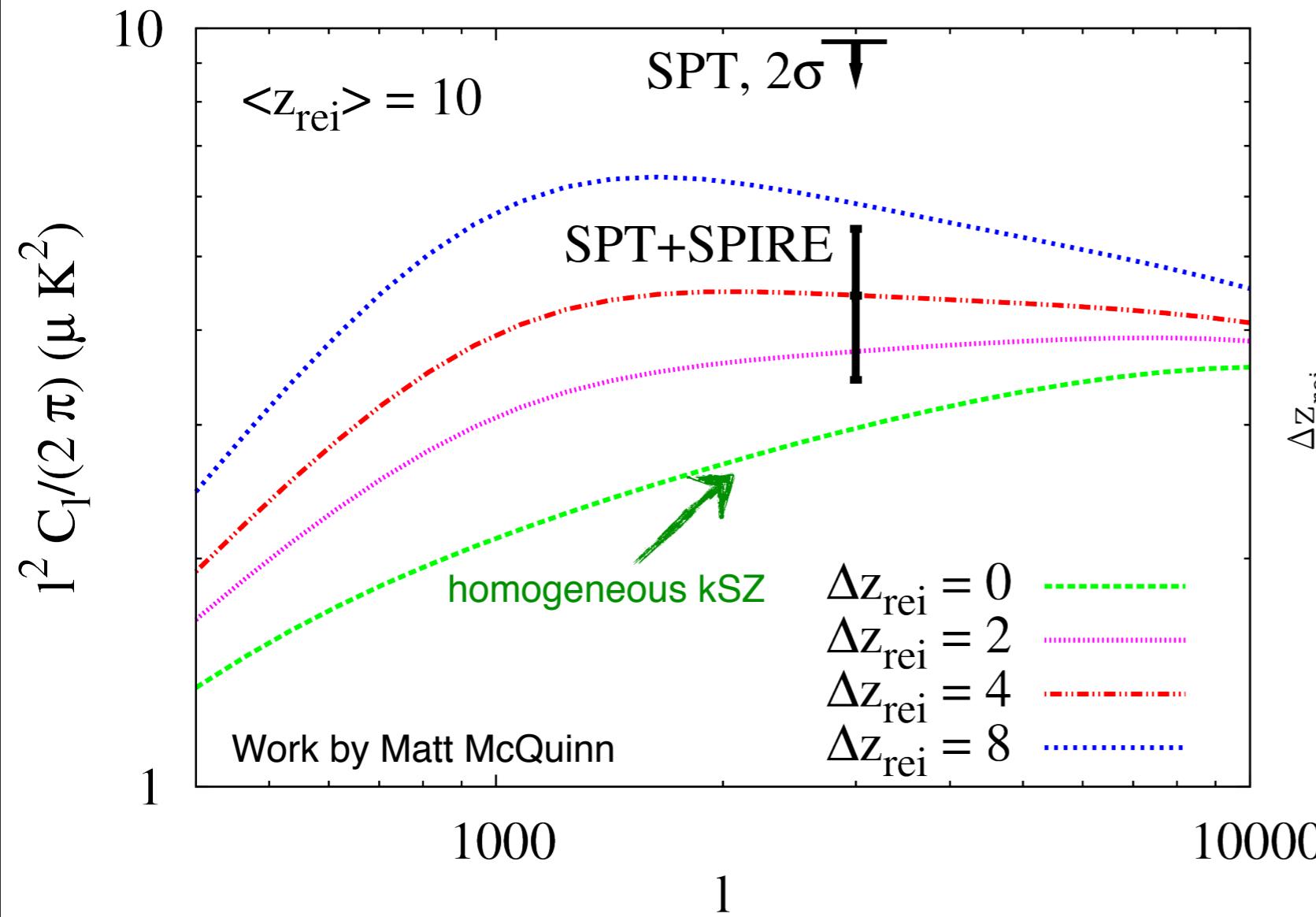
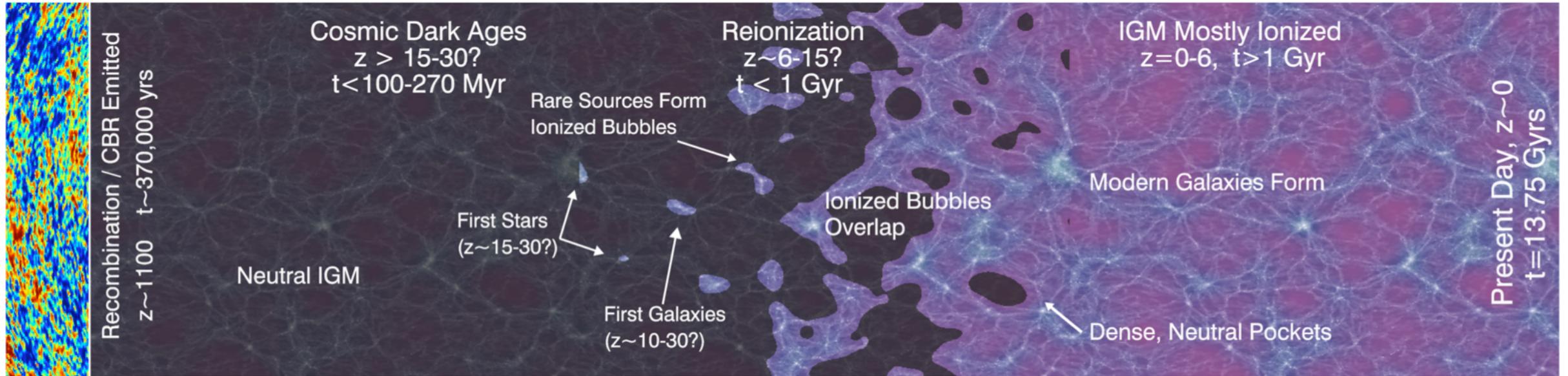


Key Questions:

- What were the sources which caused reionization?
- When did reionization occur?
- How long did the epoch of reionization last?

Cosmic Reionization

Robertson et al 2010, NATURE

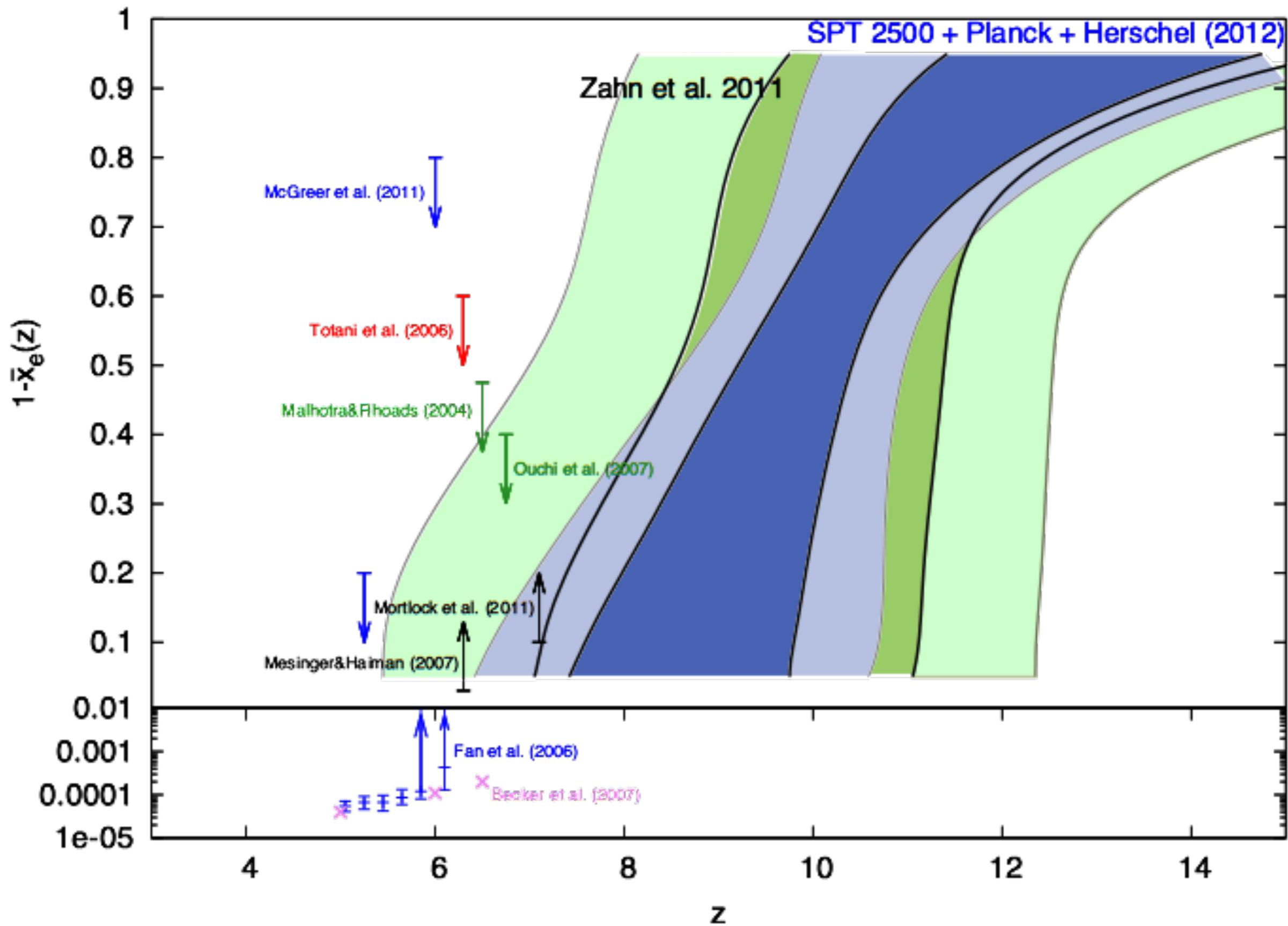


At $z \sim 30$ reionized patches and bubbles begin to form around UV sources.

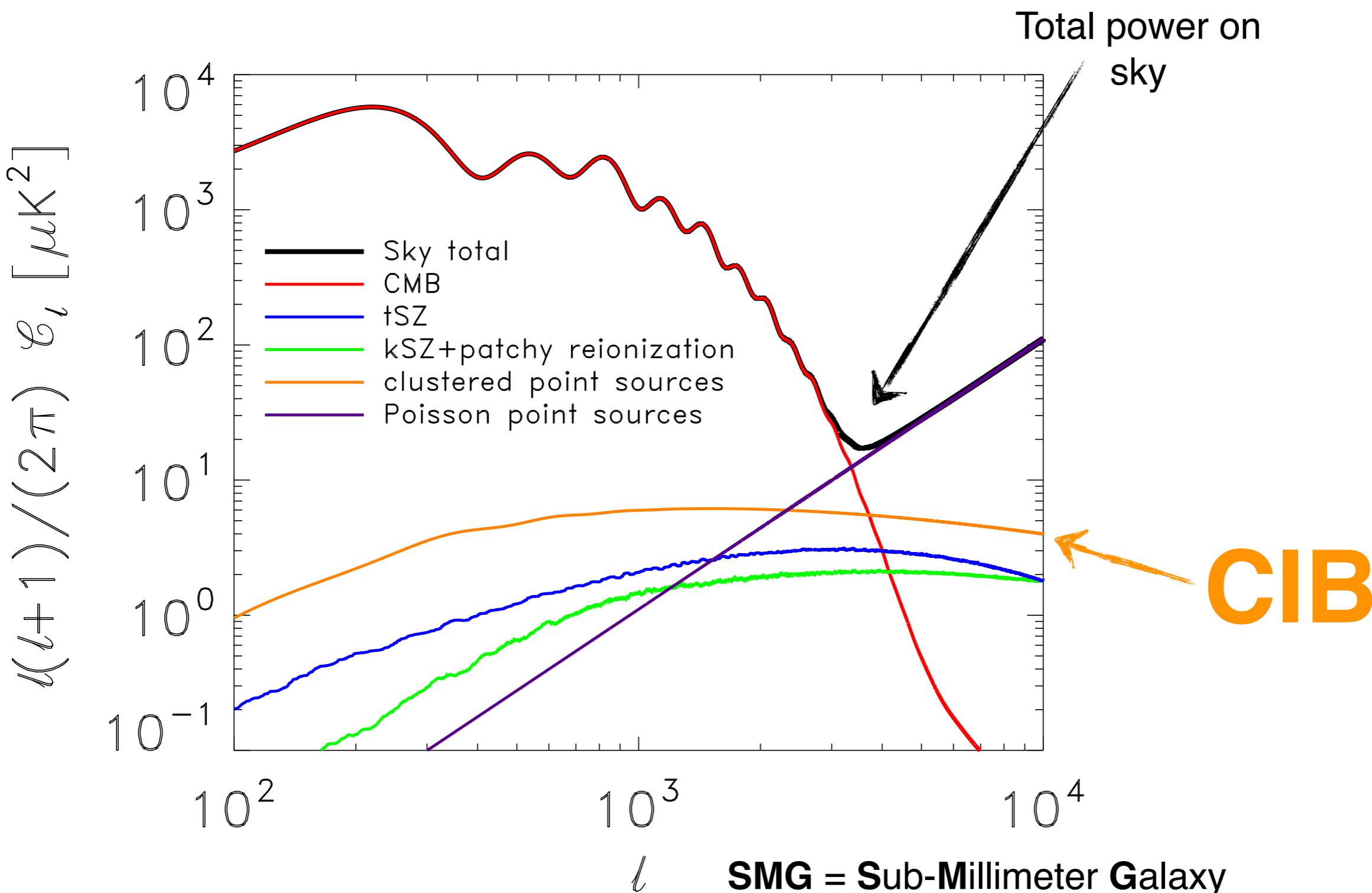
These patches are moving relative to the CMB and impart a signal onto the microwave background \rightarrow kSZ.

Strength and shape of kSZ signal depend on how the Universe became reionized and Dark Ages ended.

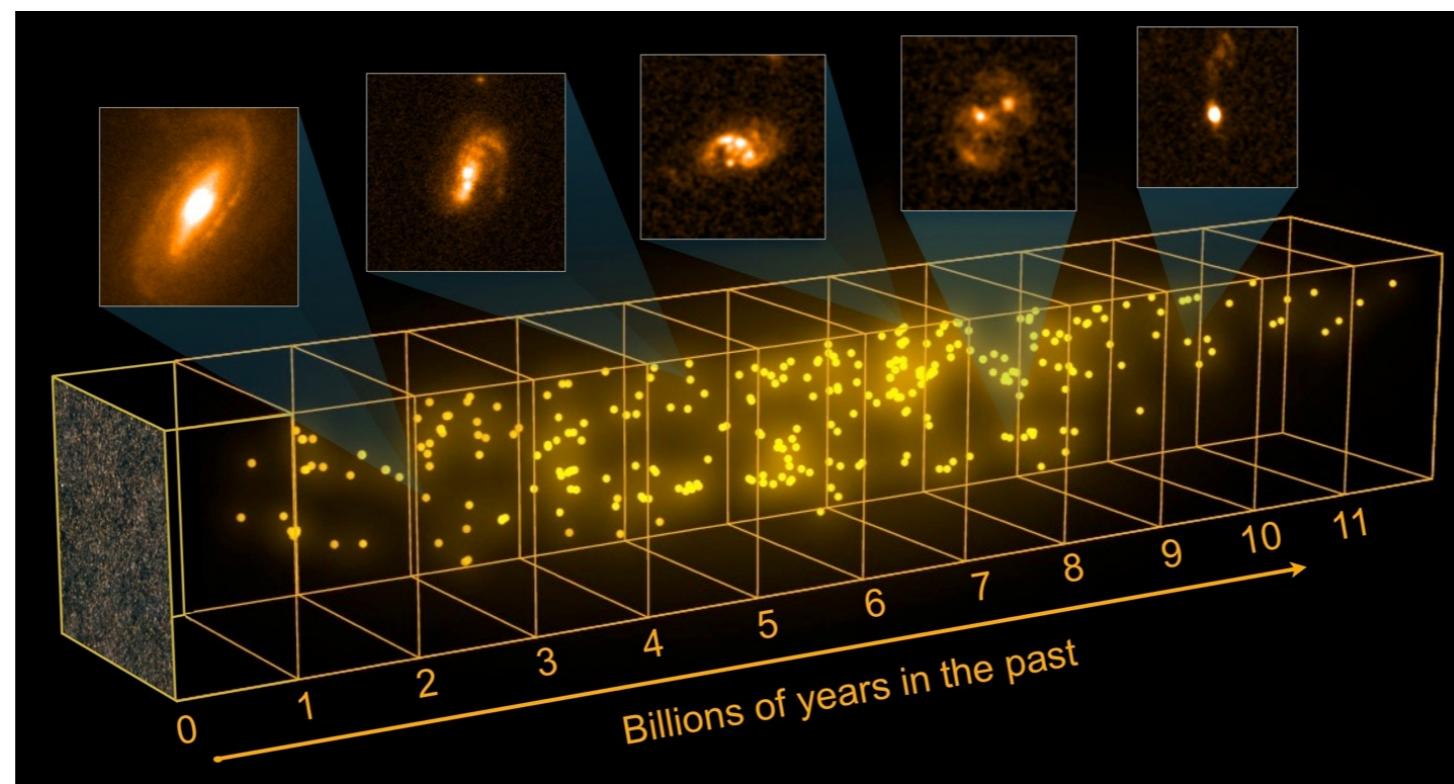
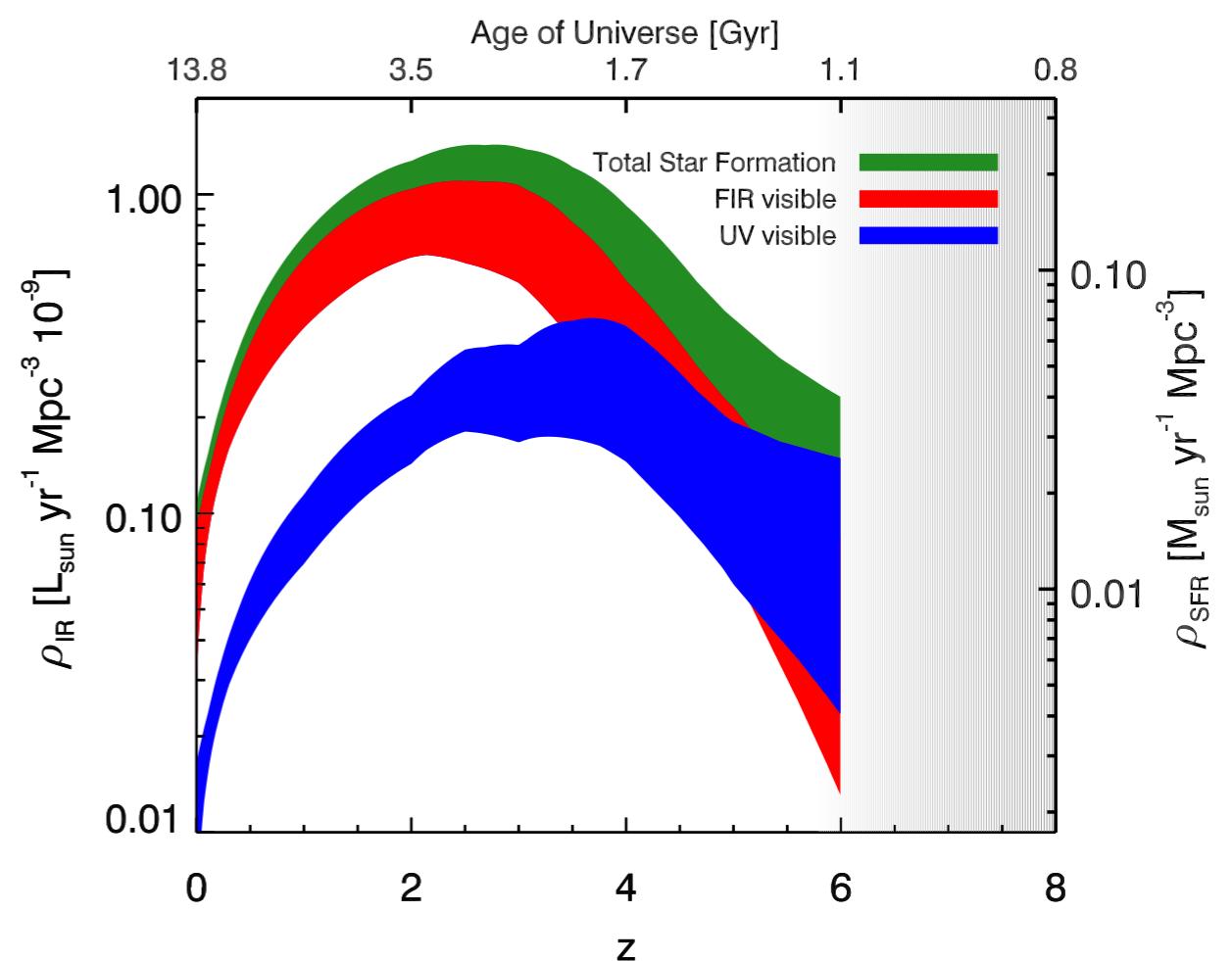
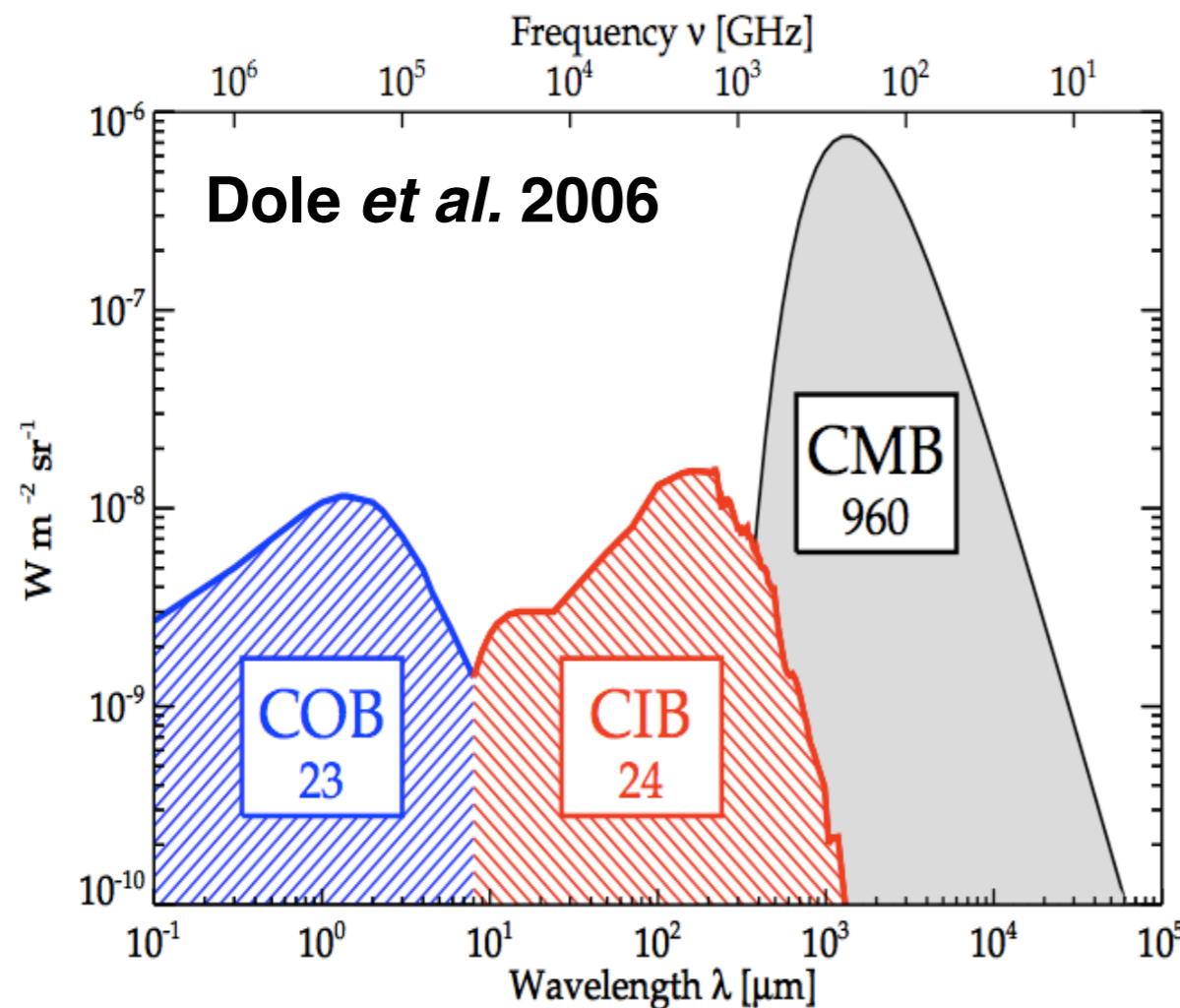
Epoch of Reionization

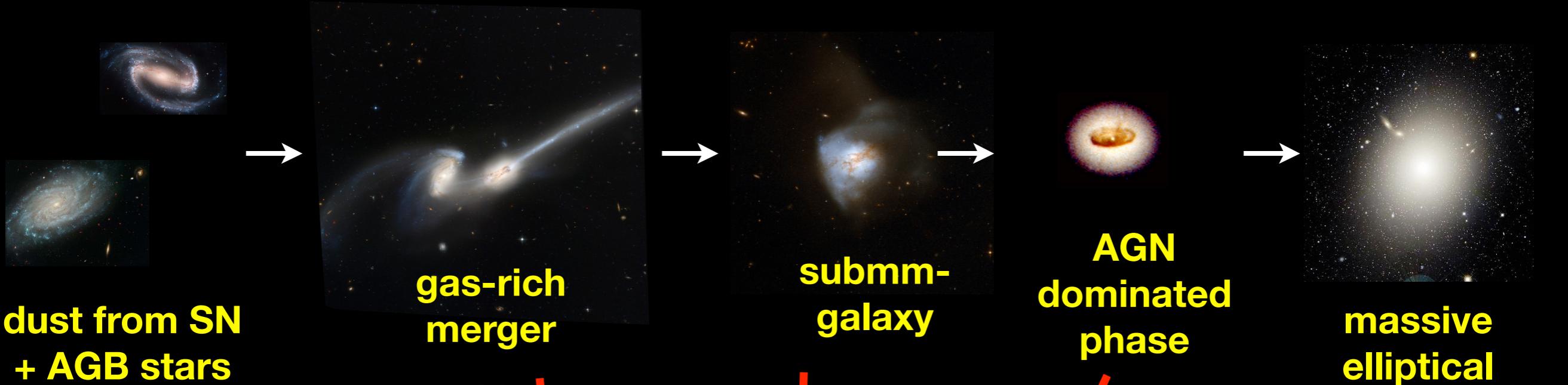


CIB



The Cosmic Infrared Background (CIB)

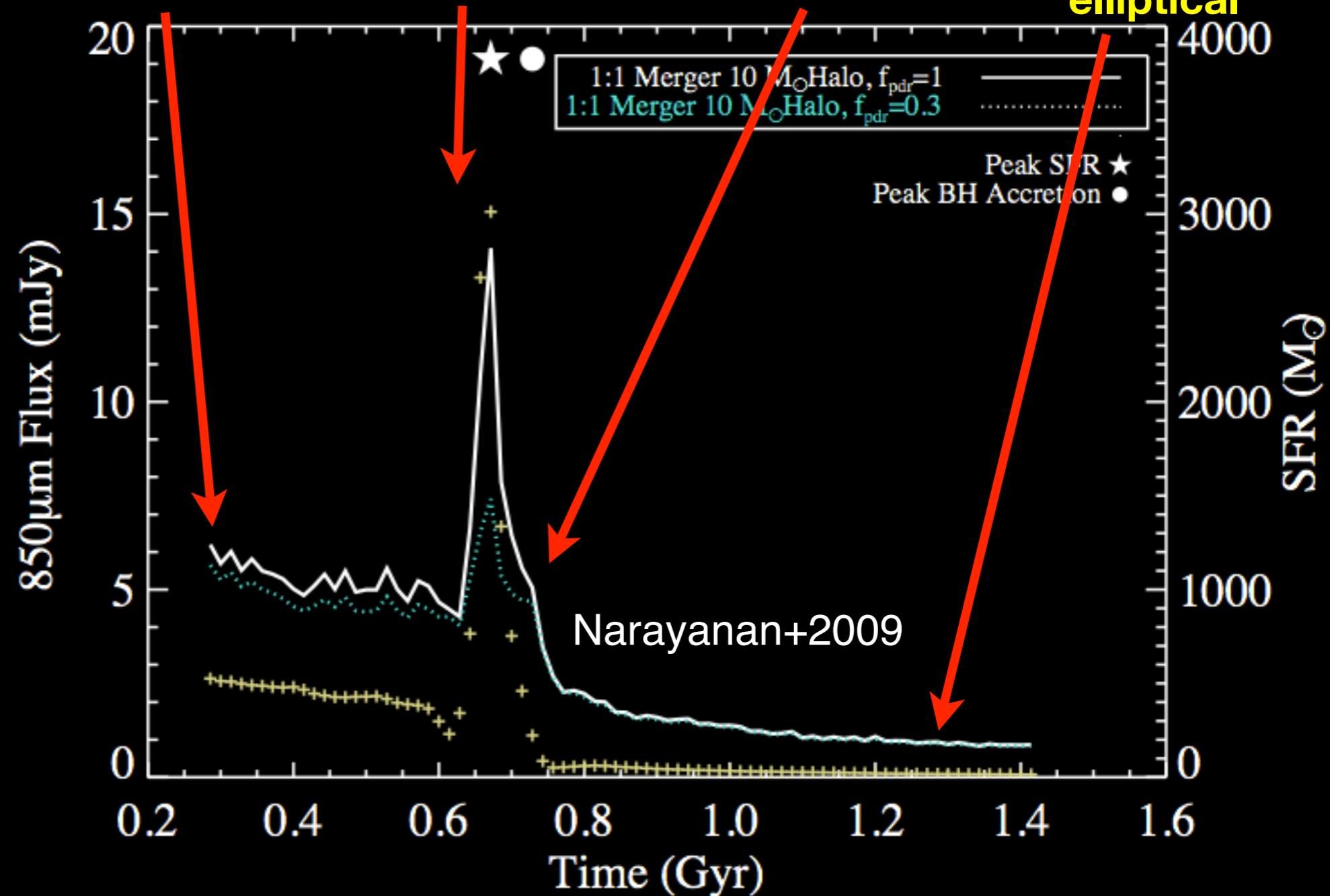




SMG = sub-millimeter galaxy

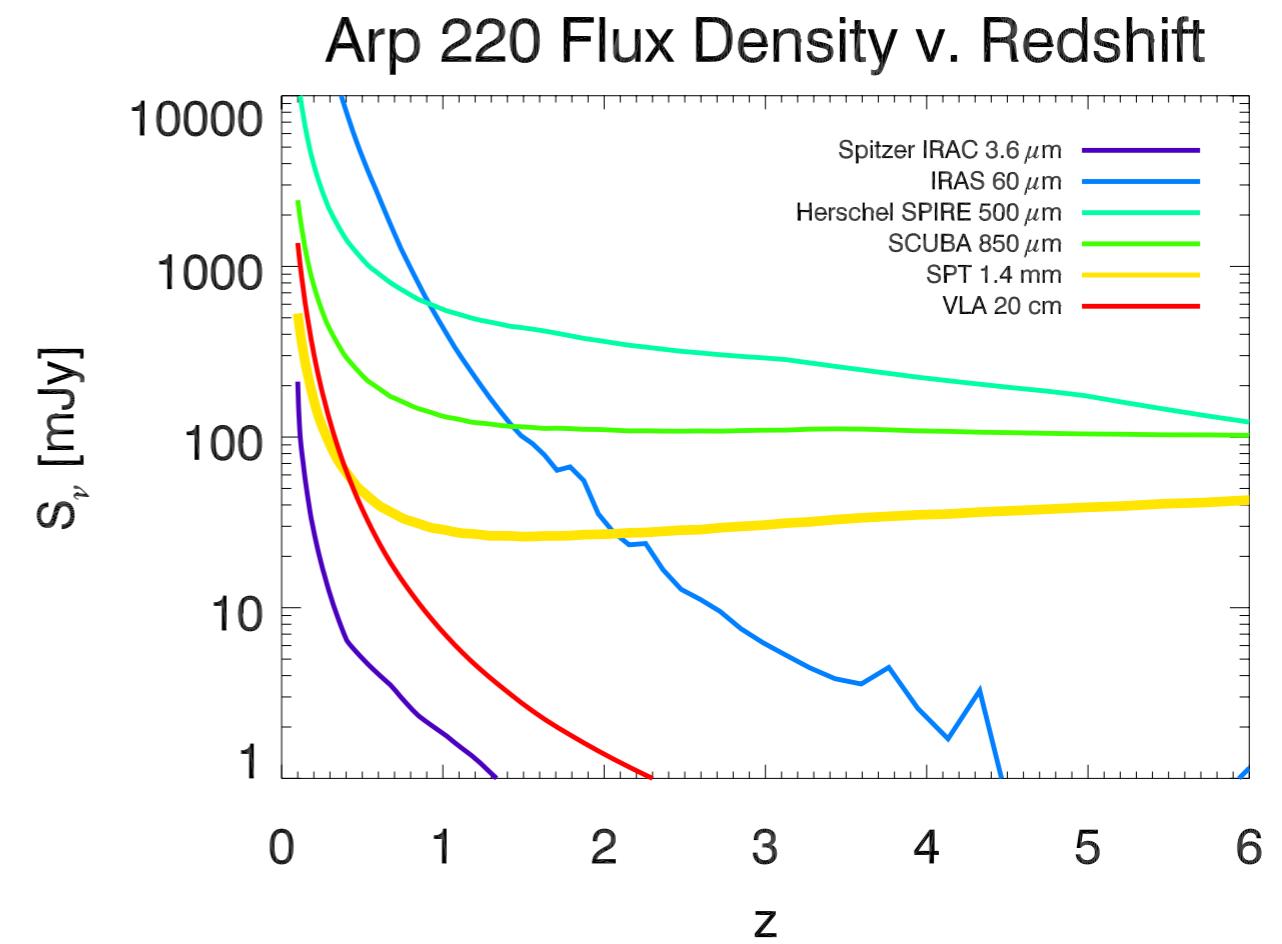
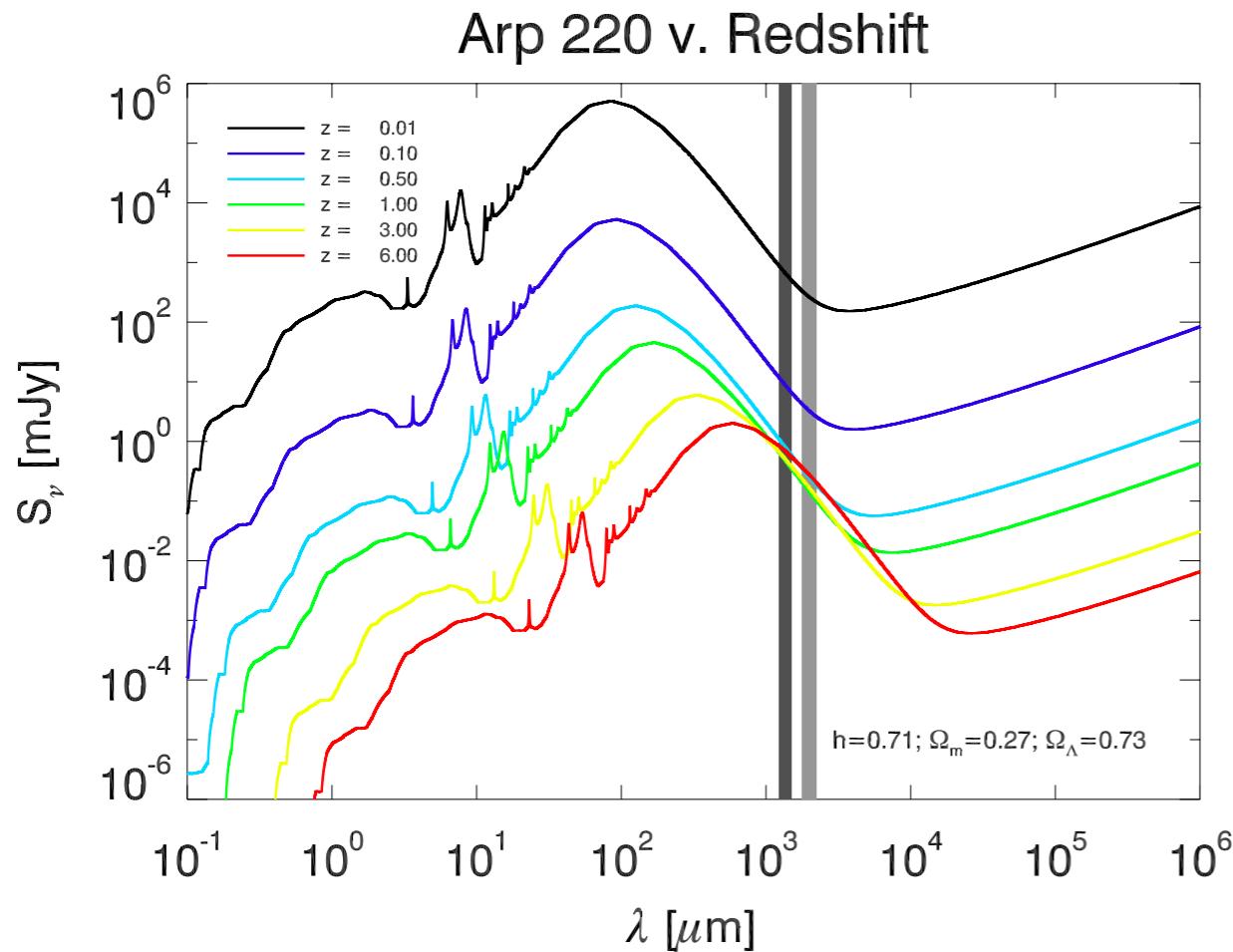
the most luminous dusty starburst galaxies at $z>1$

Theoretical model for the formation and evolution of submillimeter galaxies



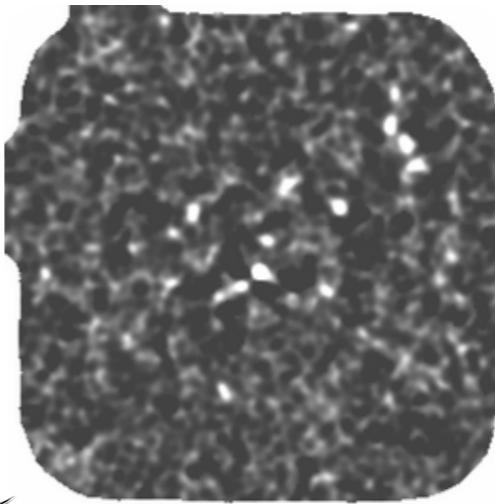
Sub-mm magic

See Franceschini *et al.* 1991 and Blain & Longair 1993



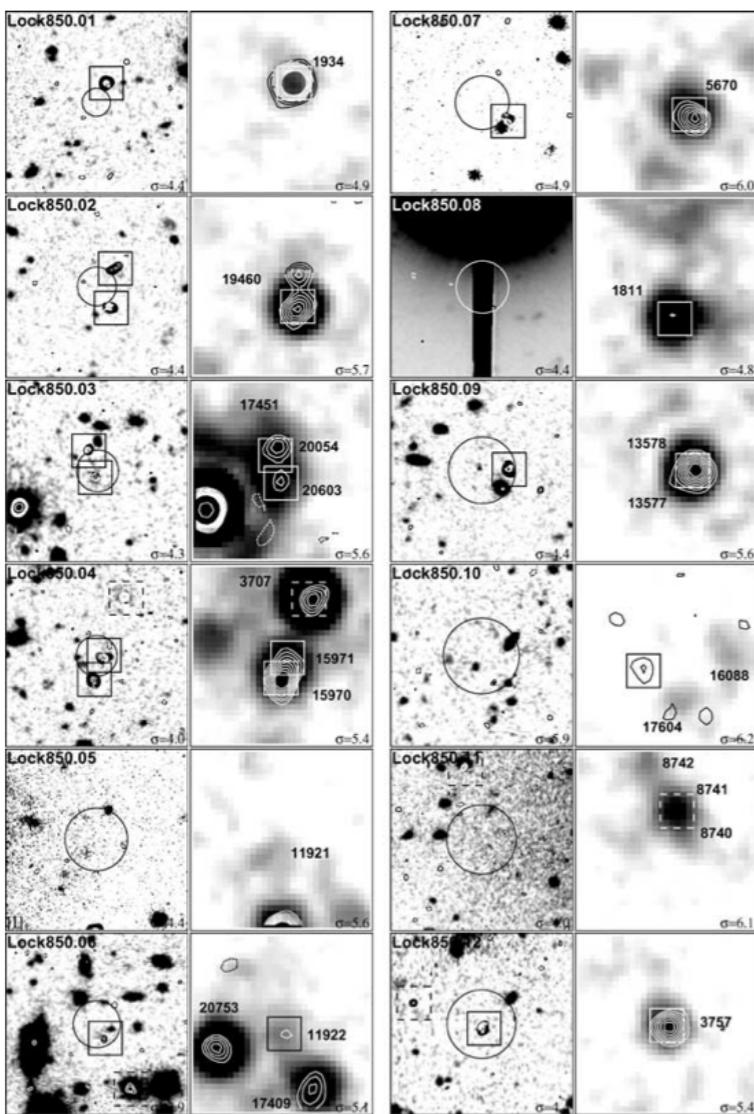
Redshifts: Good

1) Blank field submm survey

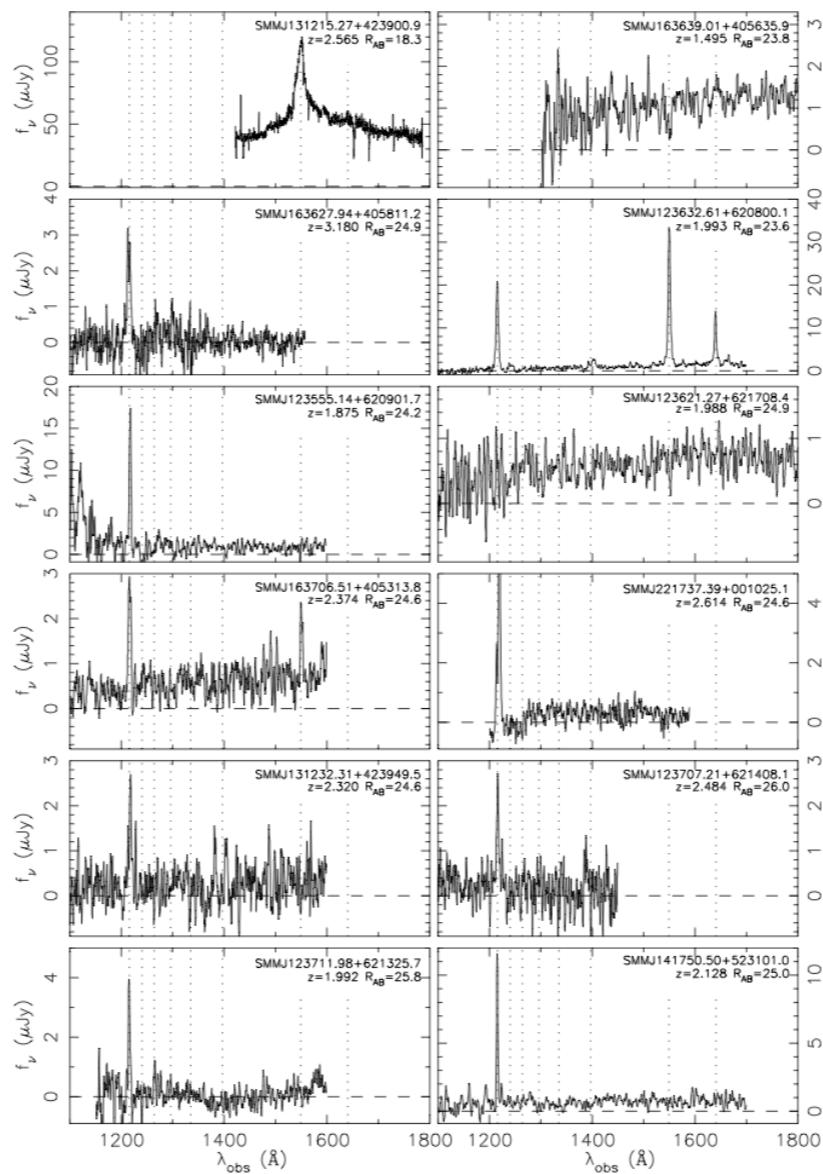


2) Find radio counterpart to SMG

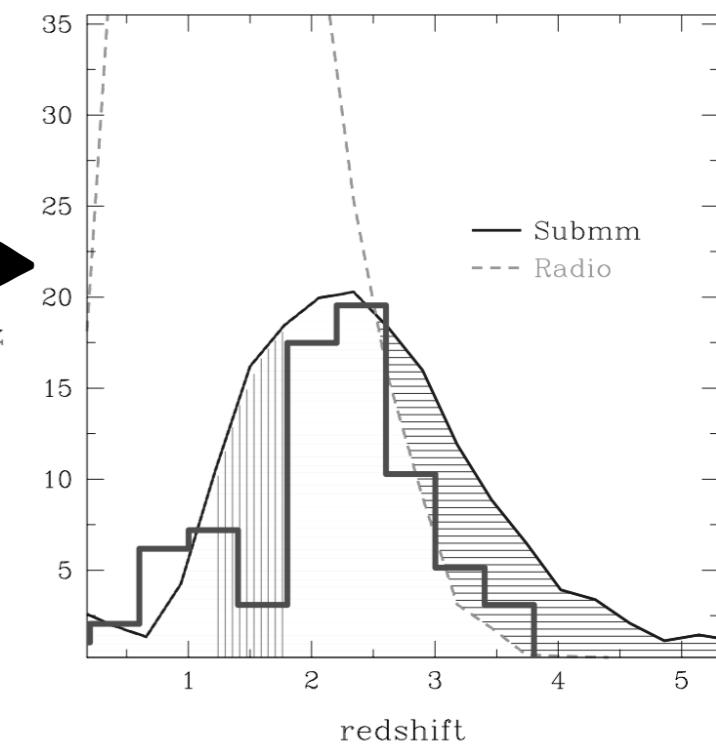
Ivison *et al.* MNRAS 2002, 2007



3) Obtain Keck spectroscopy
Chapman *et al.* Nature 2003, ApJ 2005

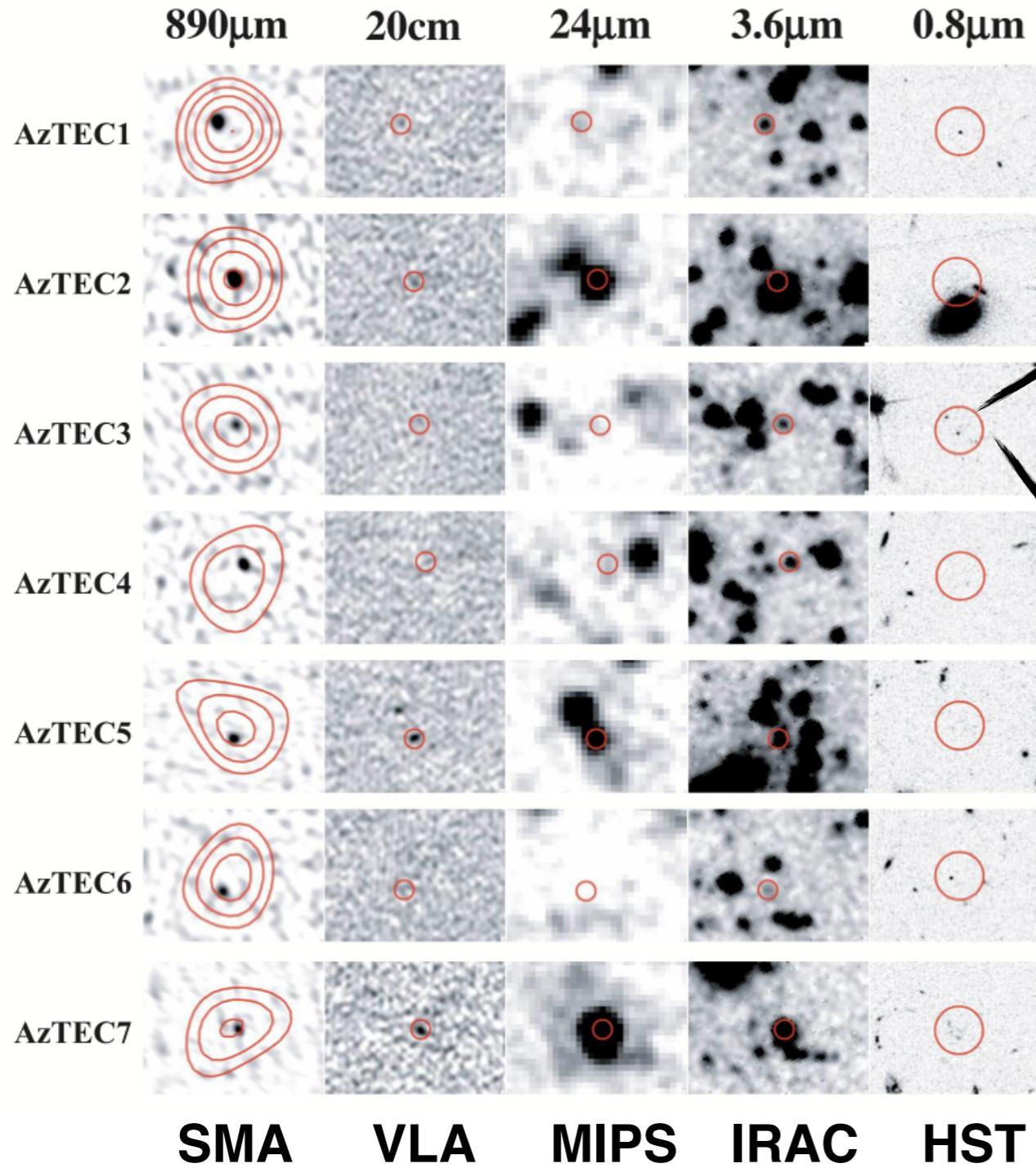


4) Estimate n(z)
Chapman et al ApJ 2005

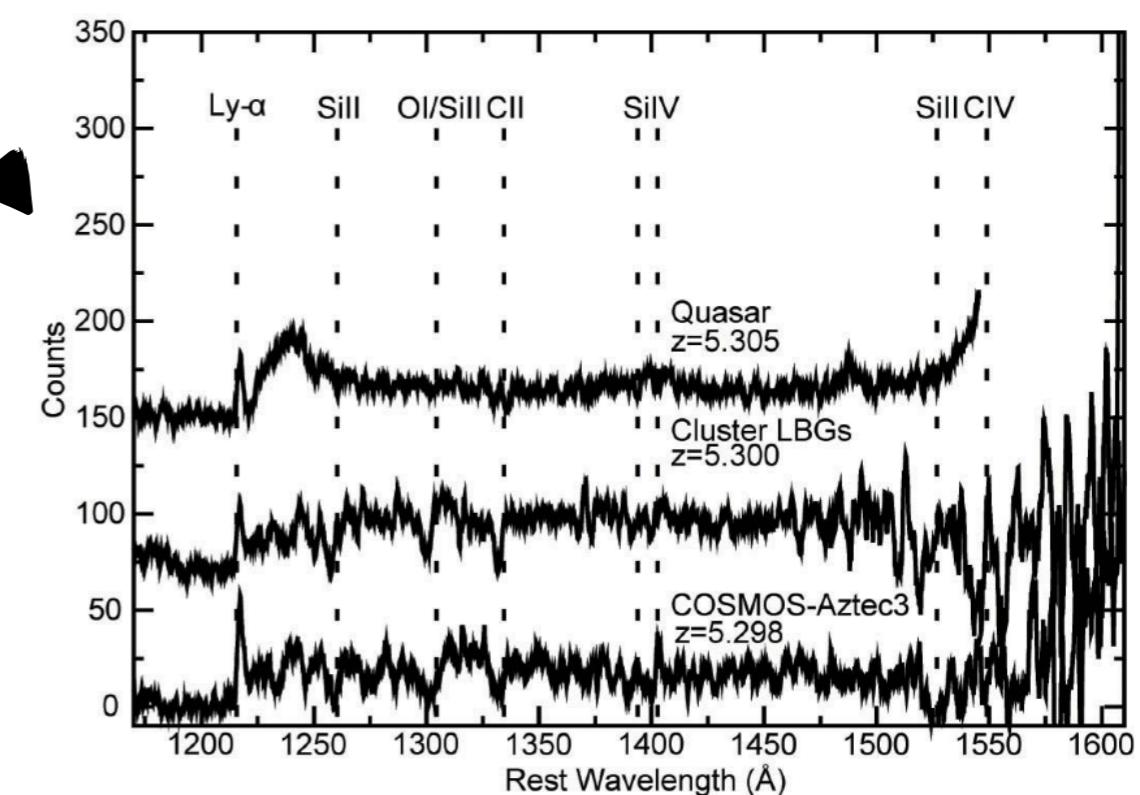
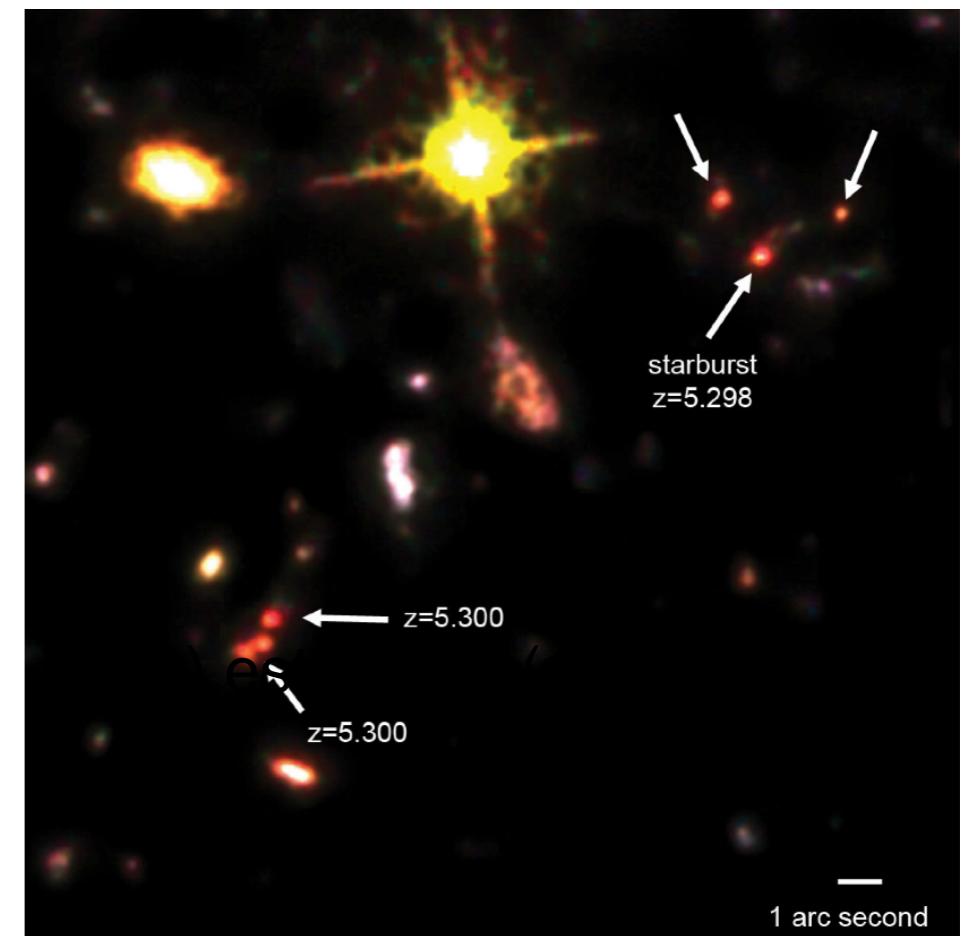


Redshifts: Better

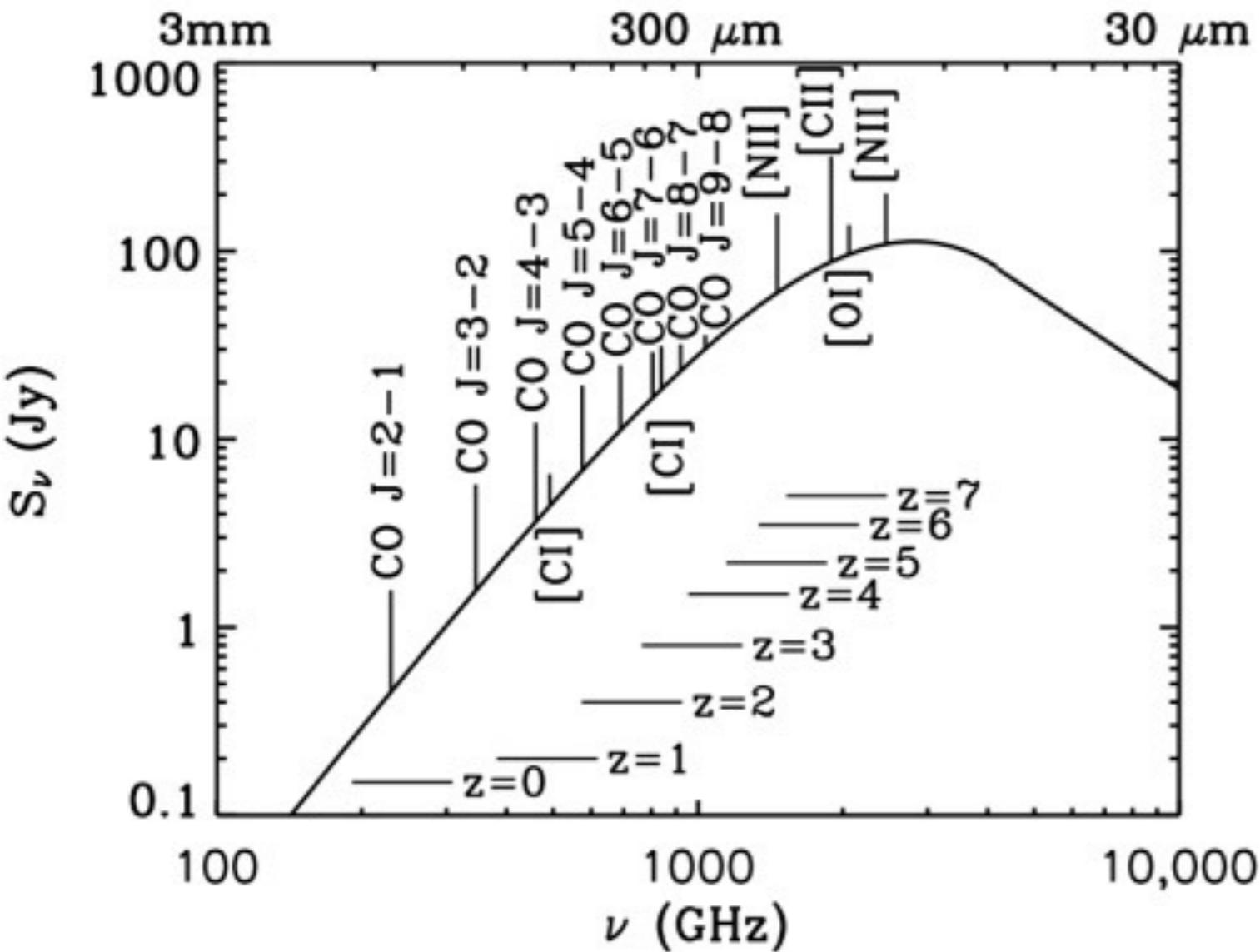
- 1) Blank field submm survey
- 2) Followup with submm interferometer
Younger et al. ApJ 2007, Smolcic et al. A&A 2012
- 3) Obtain Keck spectroscopy
Capak et al. Nature 2011



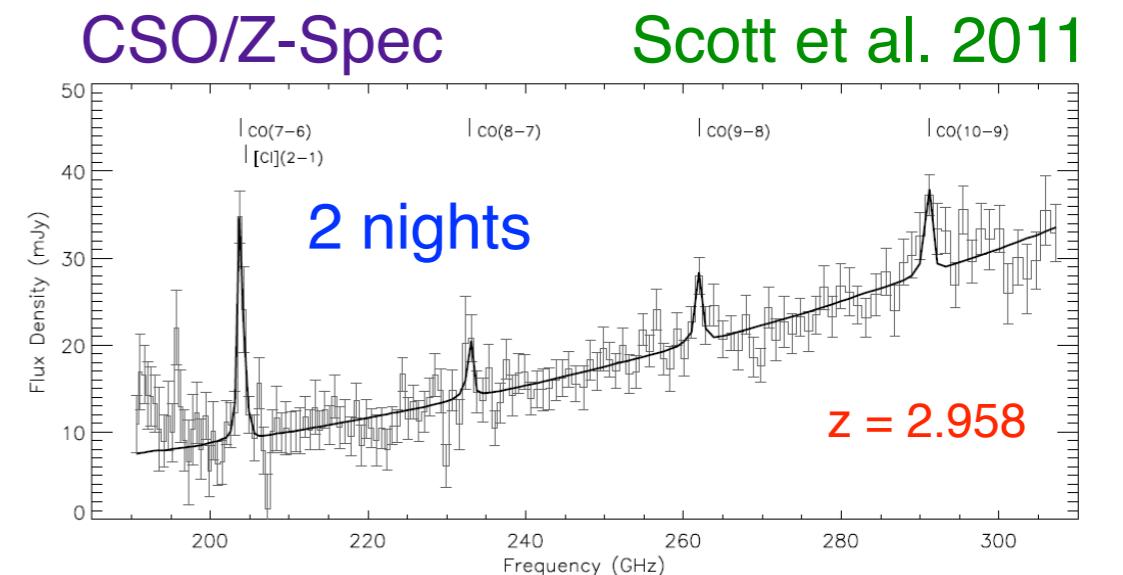
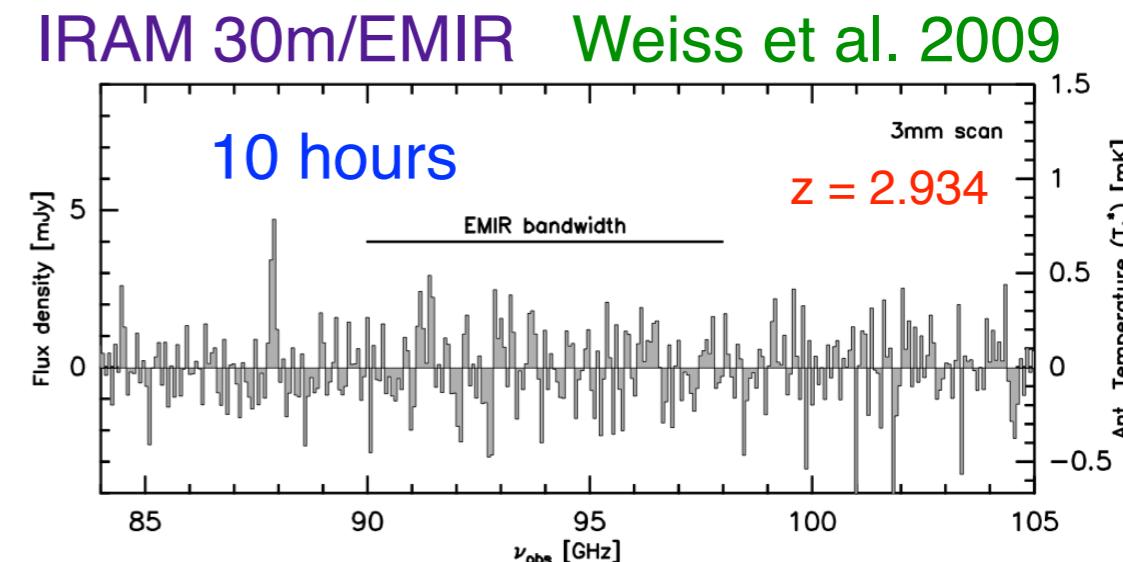
AzTEC3 $z = 5.3$



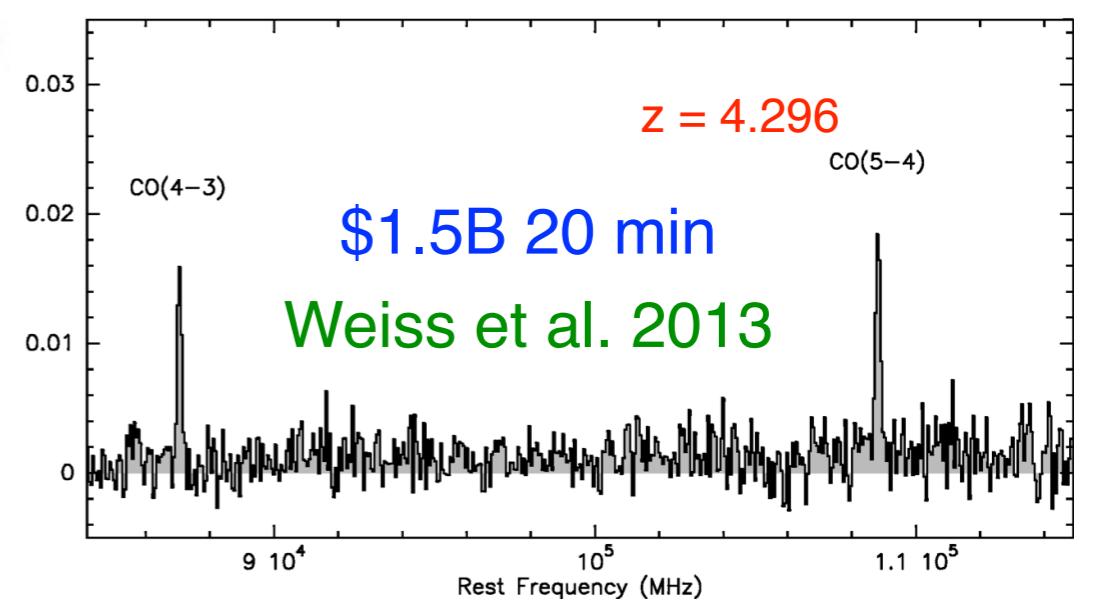
spectroscopic redshifts with carbon monoxide



- $L_{\text{CO}} / L_{\text{FIR}} \sim 10^{-5}$
- CO ladder at 115 GHz spacing → 2 lines gives a redshift
- CO traces molecular gas, dust mass
- width gives dynamical mass
- excitation ladder constrains conditions of ISM



ALMA/Band 3 SPT0345-47 @ $z=4.2957$

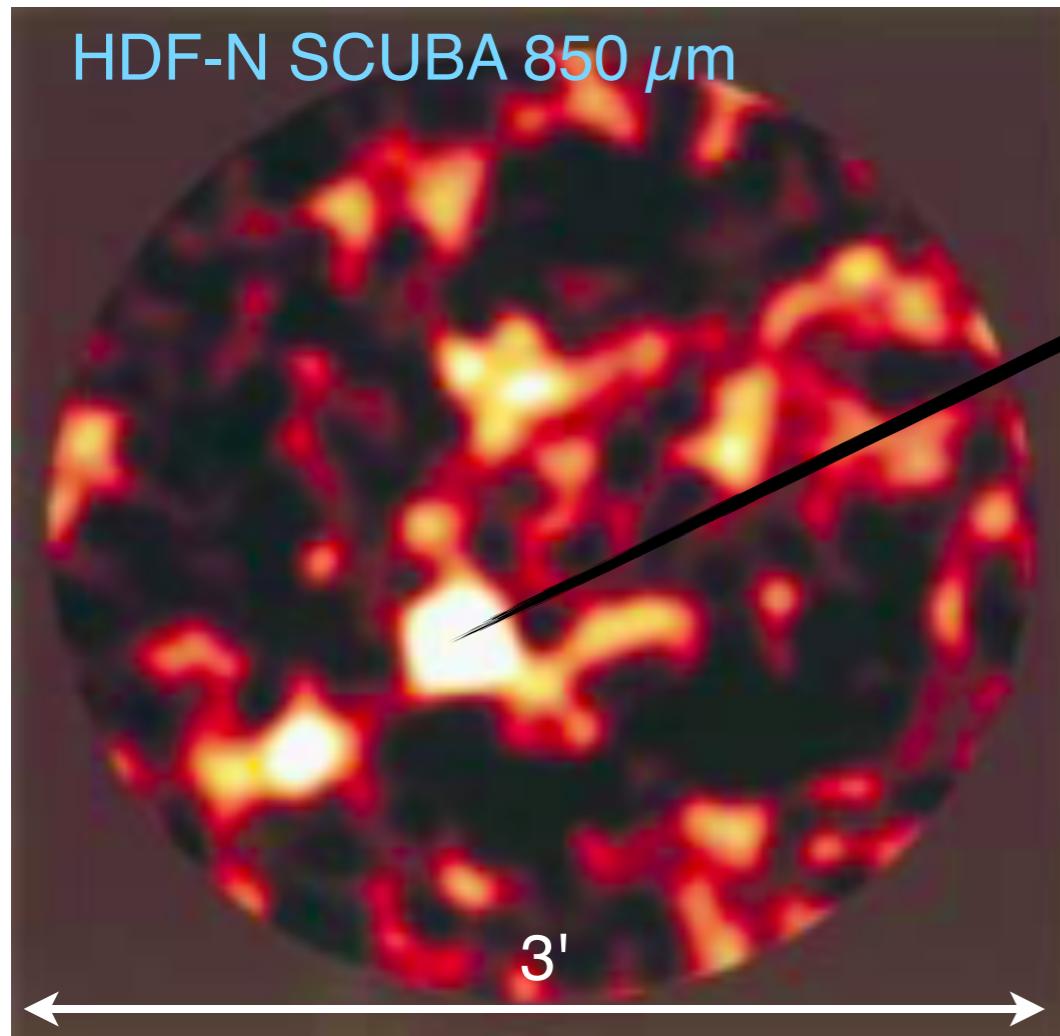


Redshifts: Best

1) Blank field submm survey

2) Followup with mm spectroscopy,
directly obtain redshifts from the dust

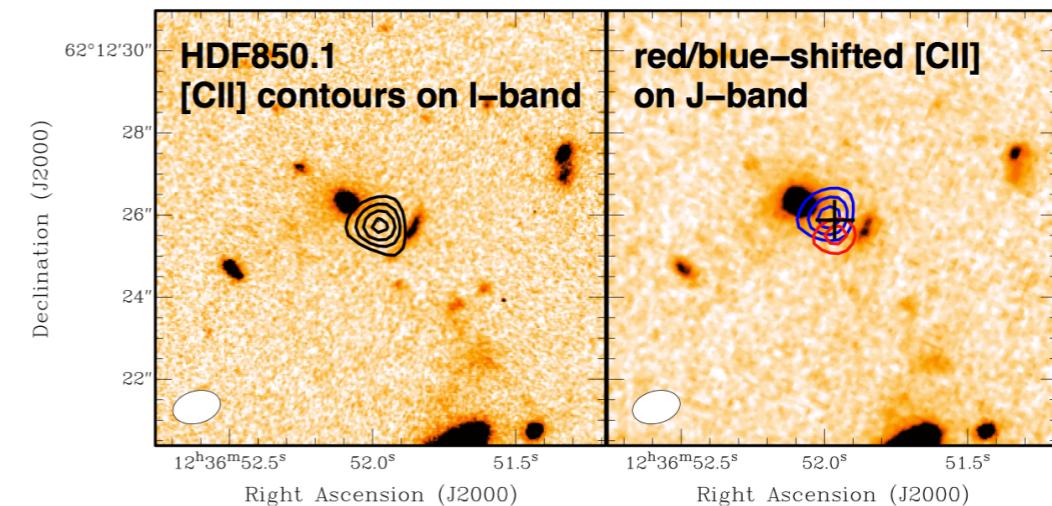
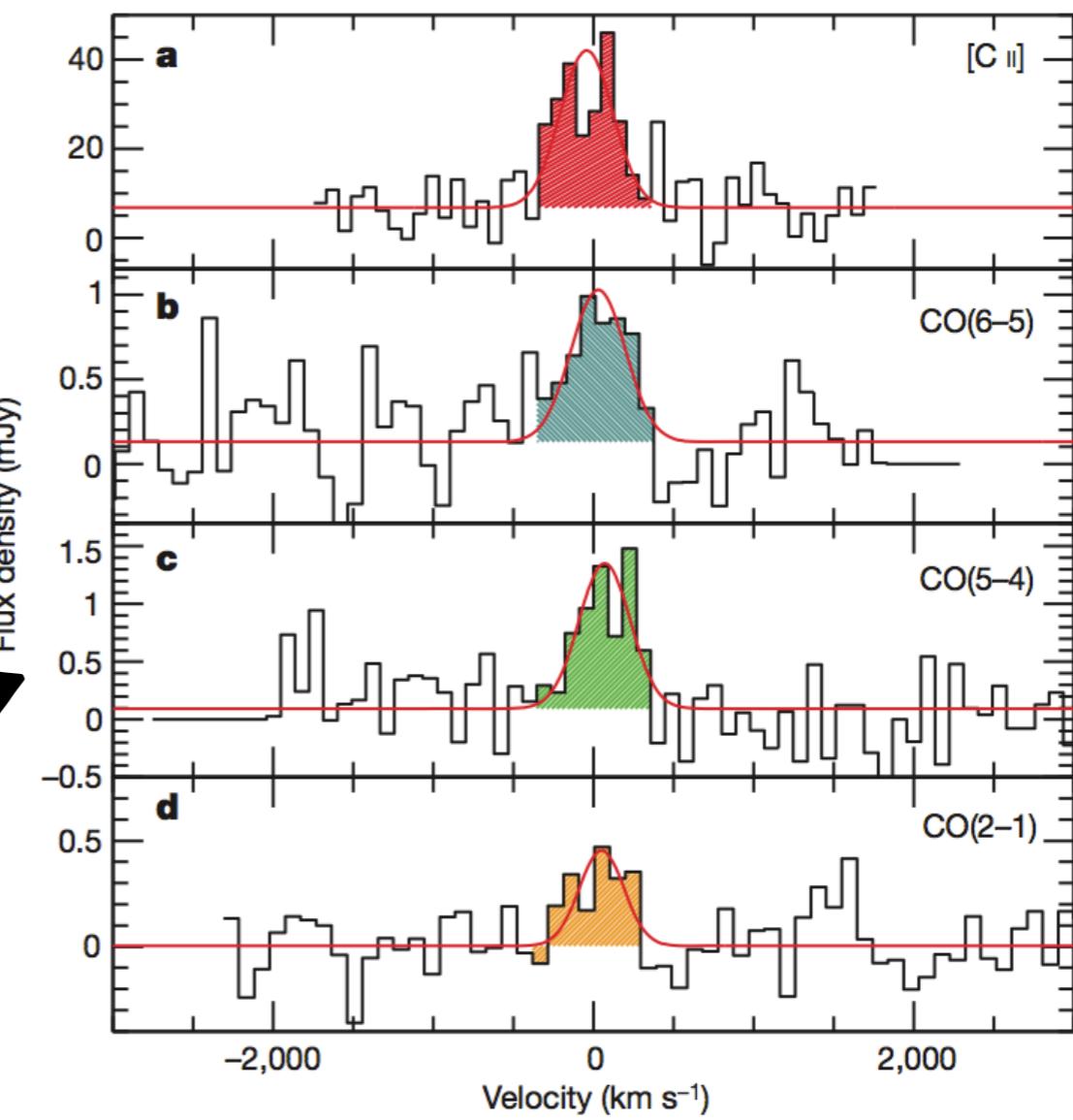
Hughes *et al.* Nature 1998



HDF850.1 $z = 5.1831$

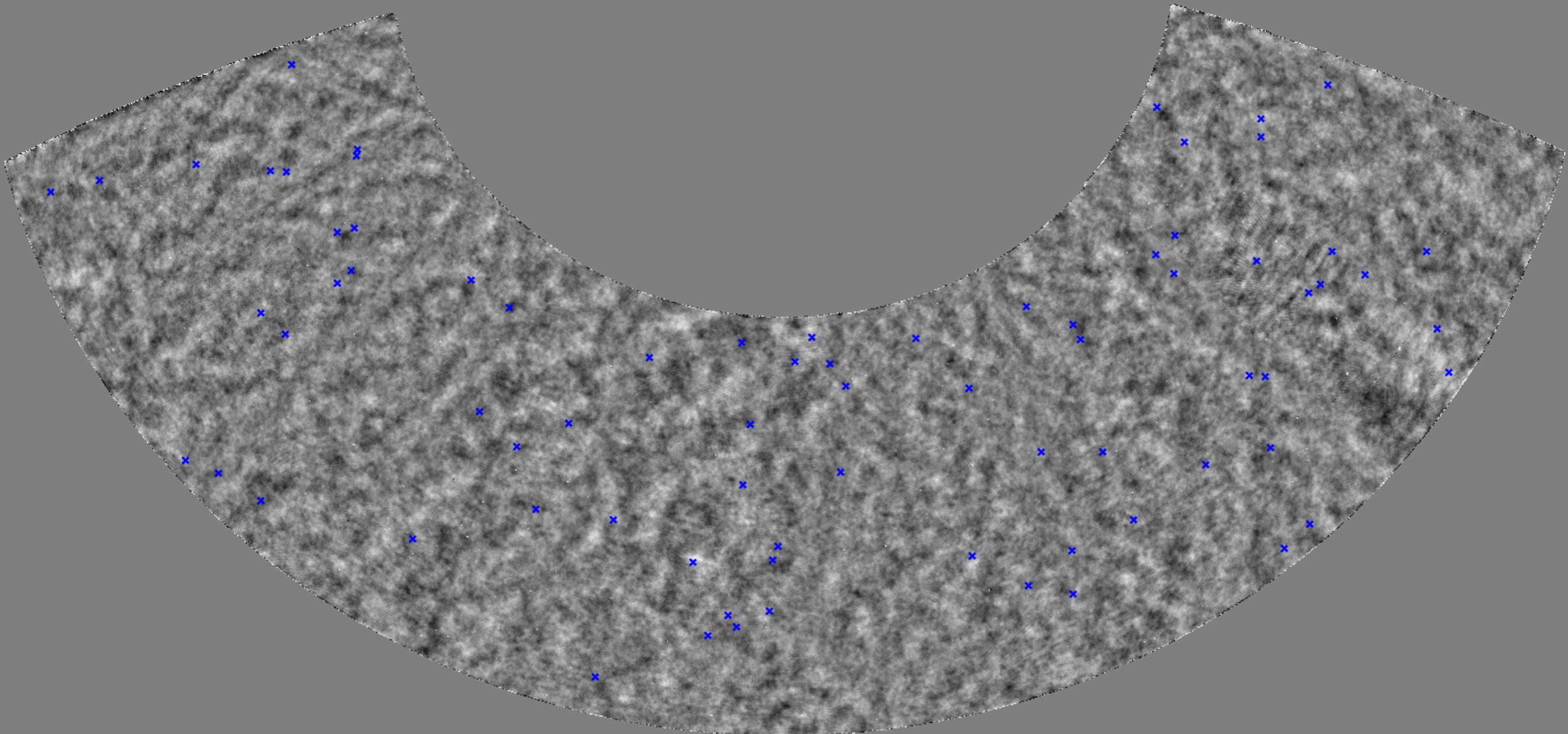
100 hours with PdBI

Walter *et al.* Nature 2012



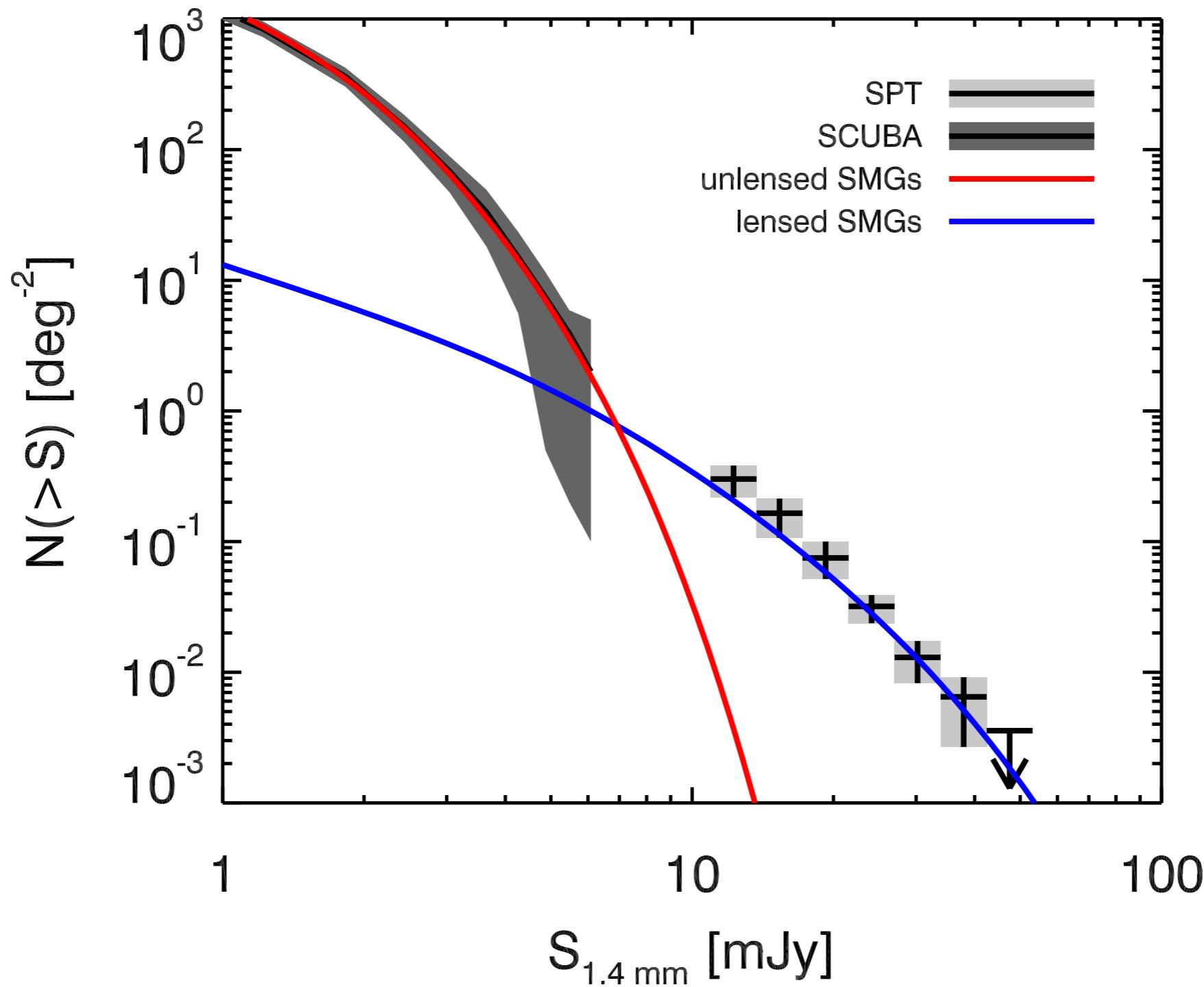
2500 deg² SPT survey

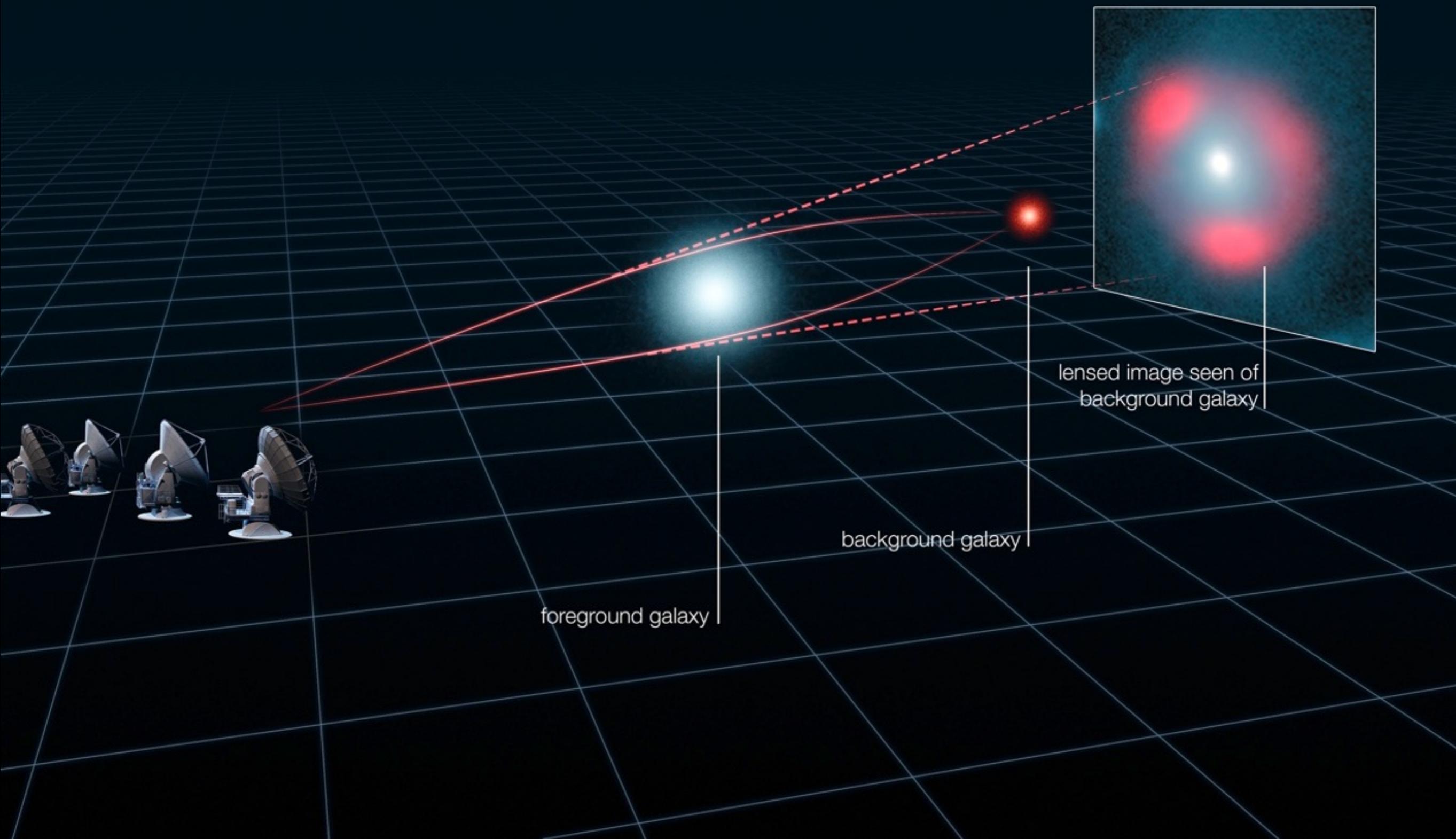
76 strongly lensed SMGs at $S_{1.4\text{mm}} > 20 \text{ mJy}$



~100 sources when we include deep fields

Could go lower in S/N and get ~200 sources, but we are already limited by the amount of telescope time we can get



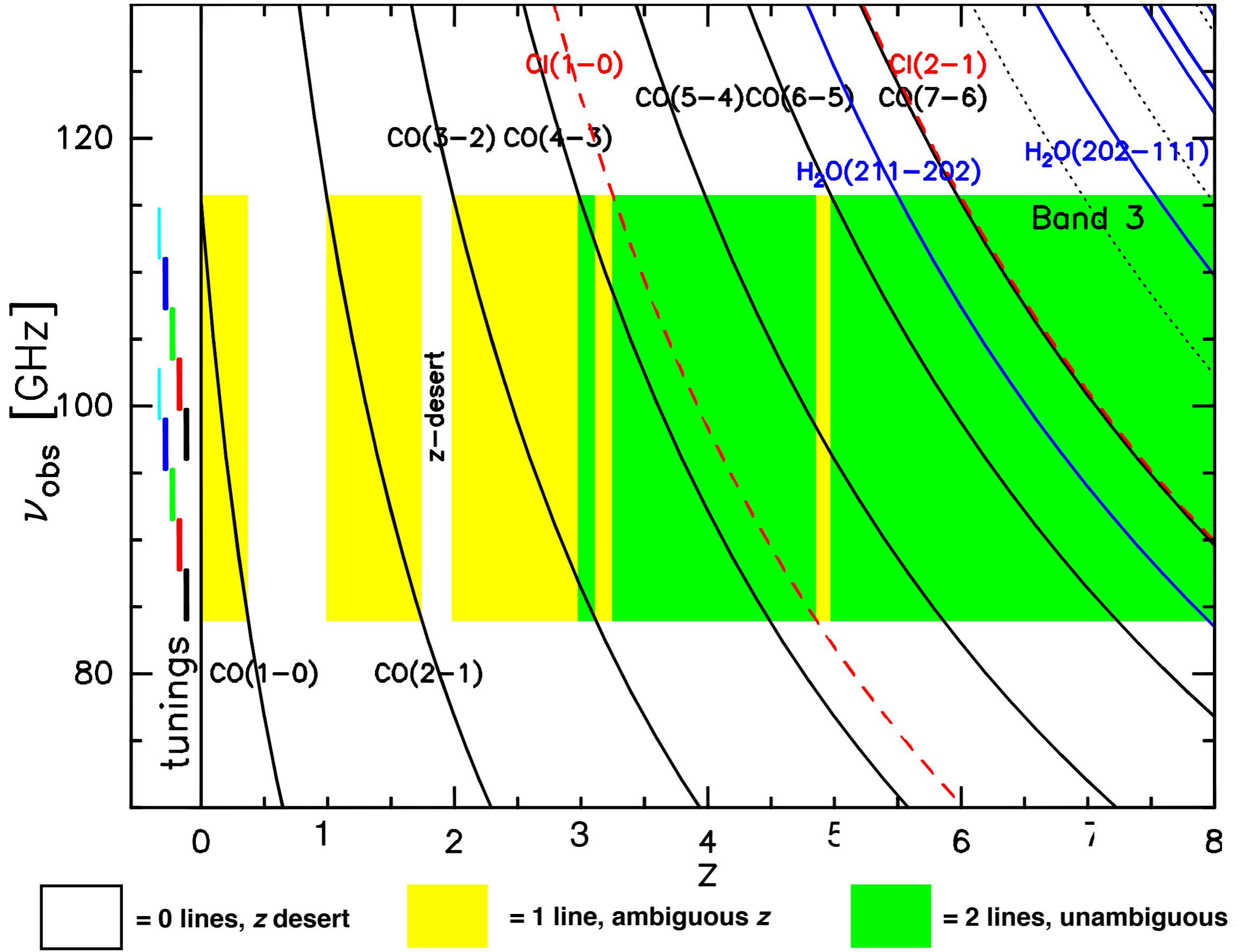


ALMA: Atacama Large (sub) Millimeter Array

- Largest ground based astronomy project of all time (~\$1.5B)
- Joint partnership between ESO, North America, Asia, and Chile
- Located at 5000m on the Atacama Plateau in Chile
- 50x12m antennas operating between 30-1000 GHz
- Resolution greater than Hubble
- Unprecedented sensitivity
- Started taking data in 2012
- First call was x10 oversubscribed

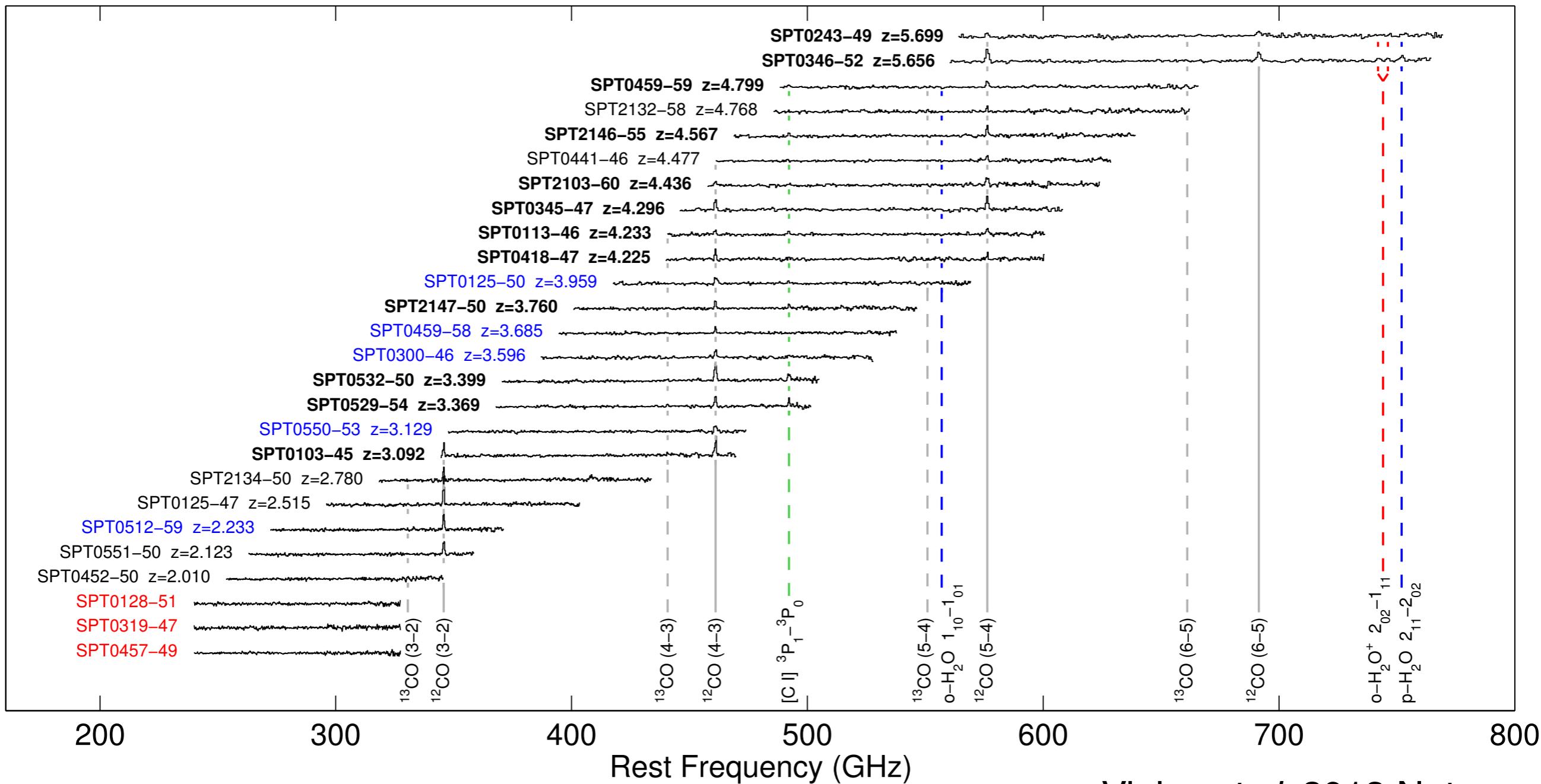


SPT+ALMA CO z -search



First spectroscopic redshift survey with ALMA

ALMA Cycle 0 Band 3
 100 GHz compact configuration
 26 sources
 5 tunings in the 3 mm band
 10 minutes per source



Bold = unambiguous redshift from ALMA

black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

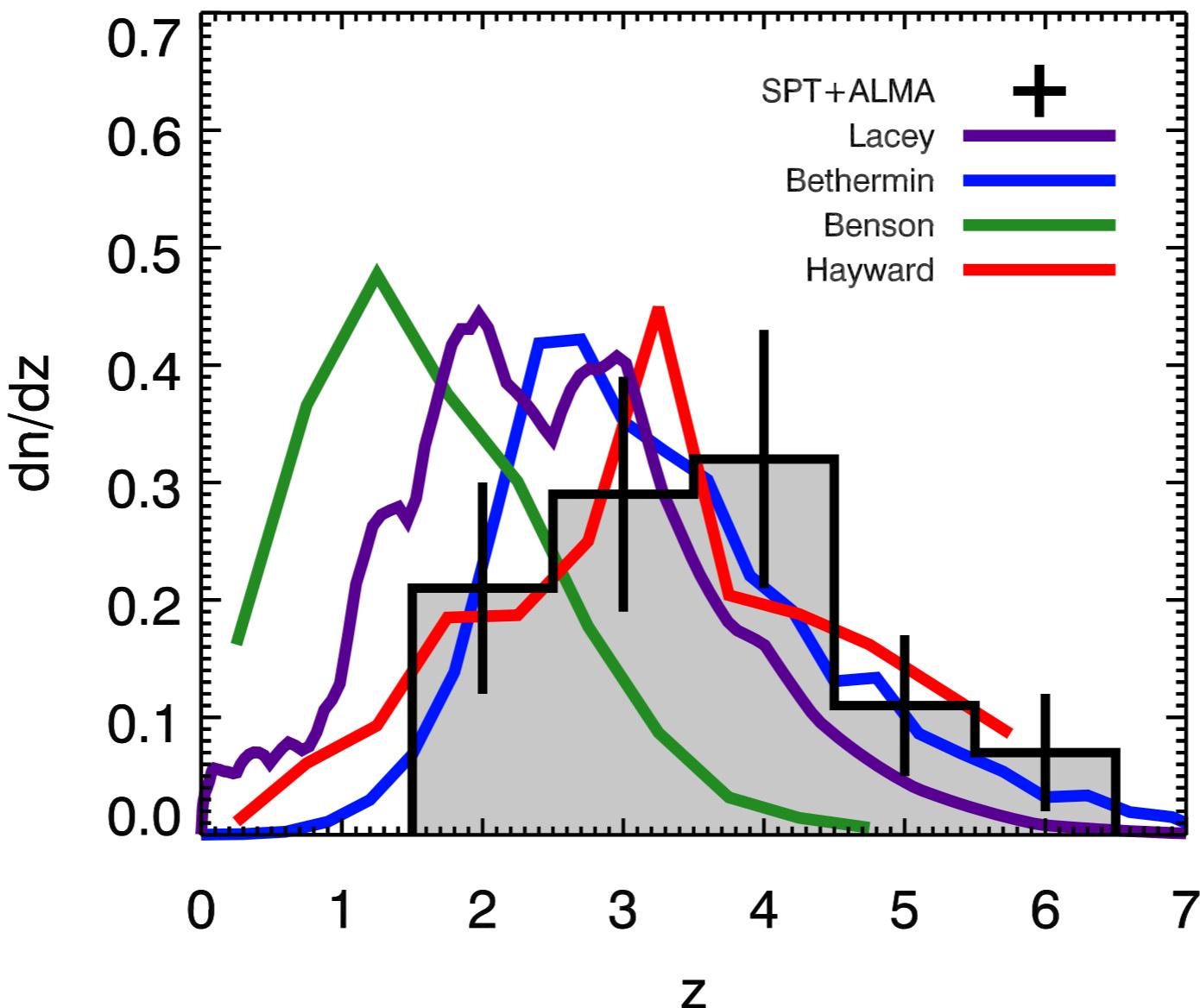
blue = single line detected with redshift, most likely redshift from photo-z

red = no line detected

Vieira *et al.* 2013 Nature

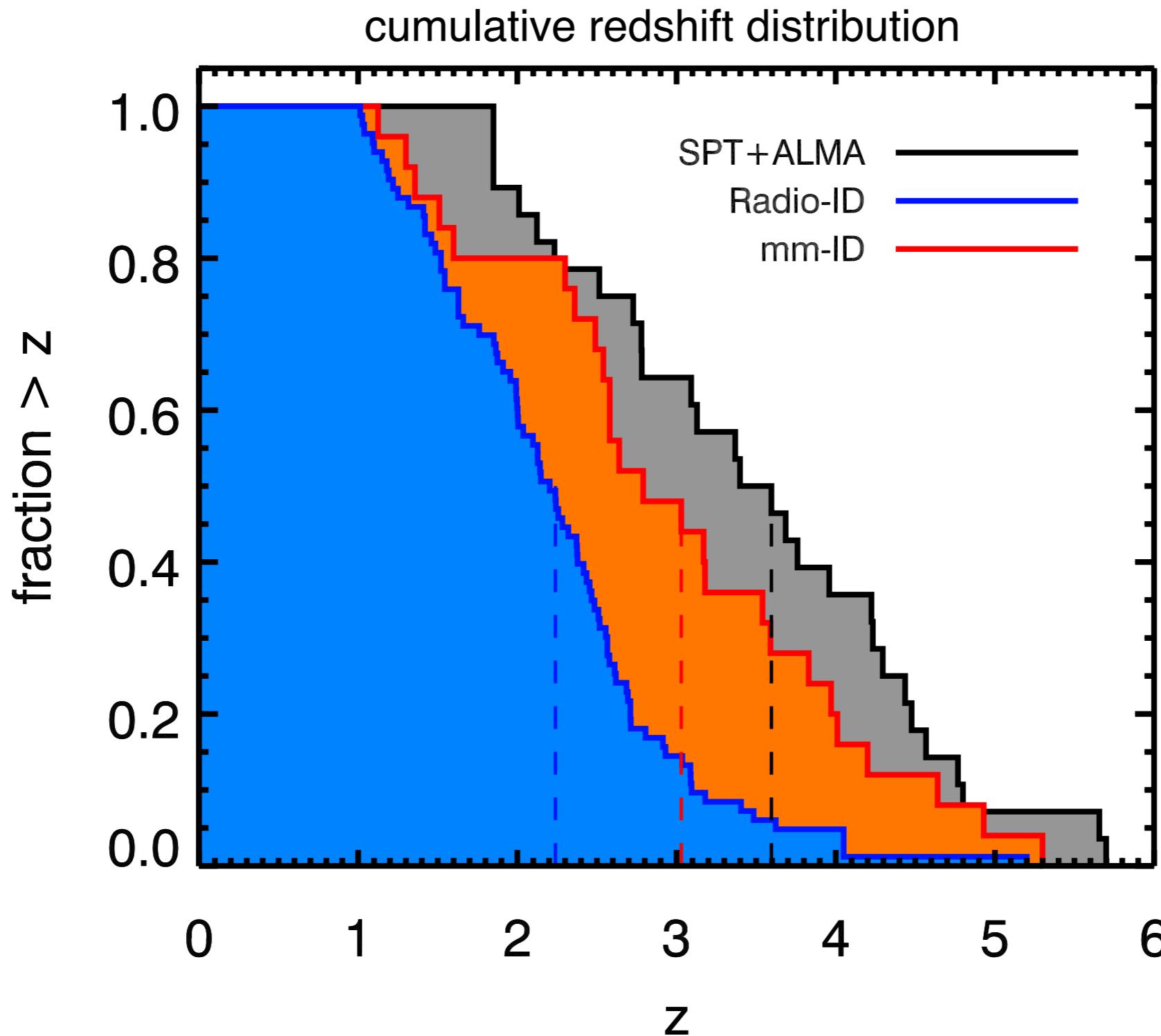
SPT+ALMA redshift distribution

Weiss *et al.* 2013 ApJ



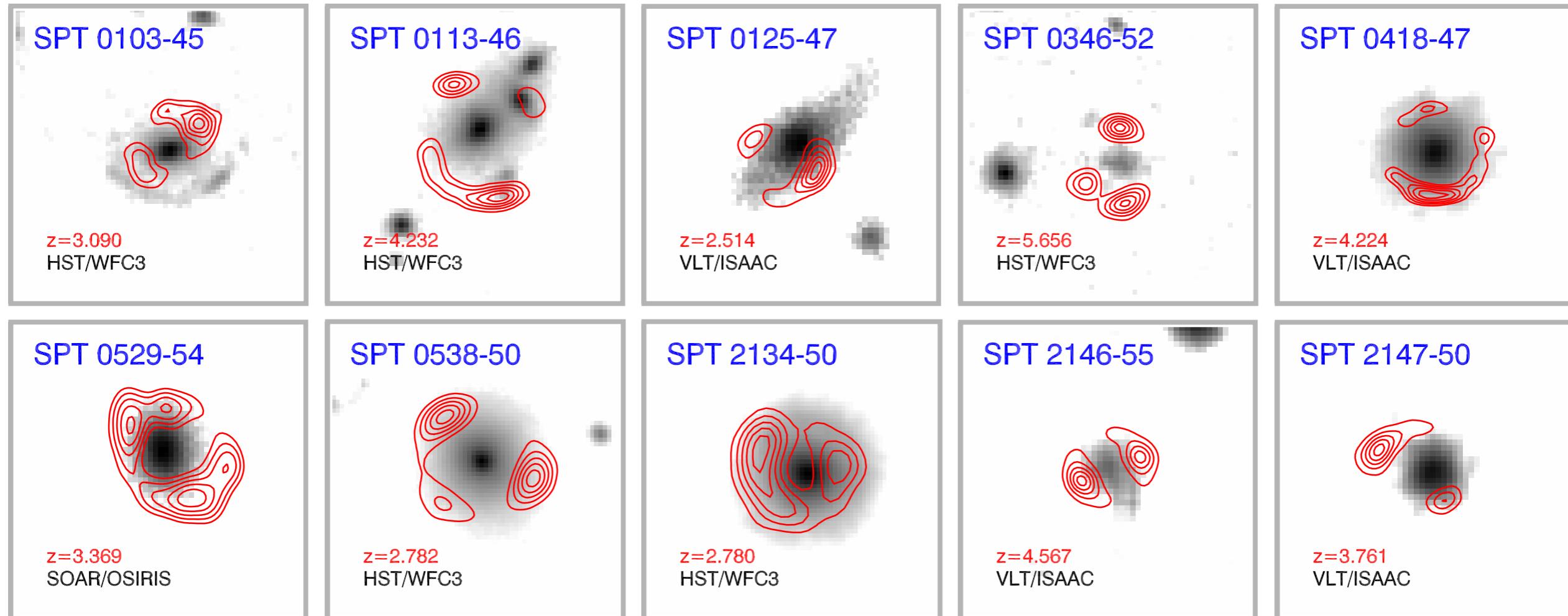
- We have a well-defined selection function based off of a uniform flux cut
- We obtained redshifts for 90% of sources without any additional selection biases
- This redshift distribution already provides powerful constraints for models of galaxy evolution

SPT + ALMA n(>z)



Vieira *et al.* 2013 Nature

ALMA Cycle 0 Band 7 350 GHz 2 minute snapshots



8" x 8" boxes

■ = deep NIR imaging
■ = 2 minute ALMA 350 GHz snapshot

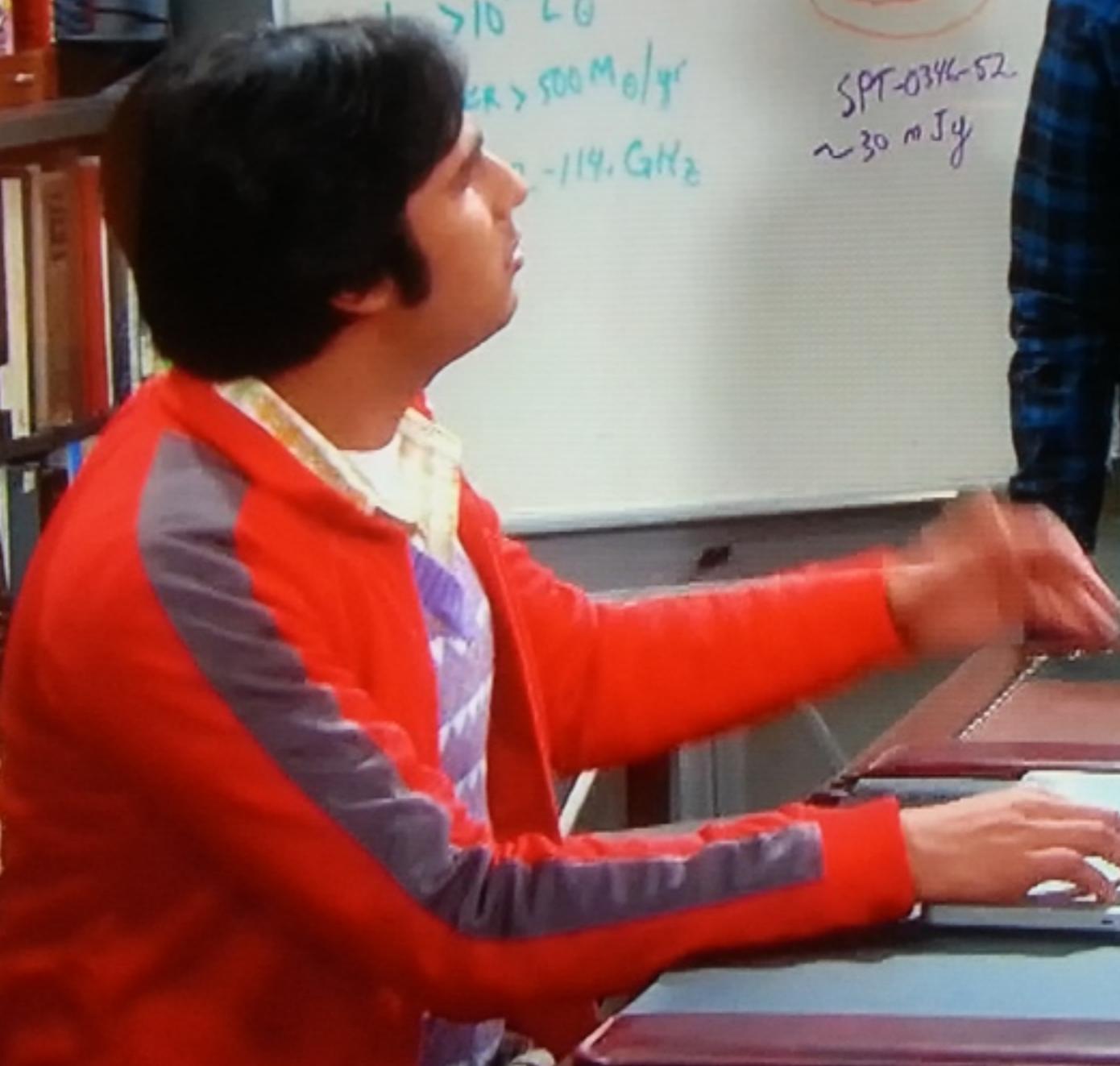
Herschel: 500, 350, 200 μm

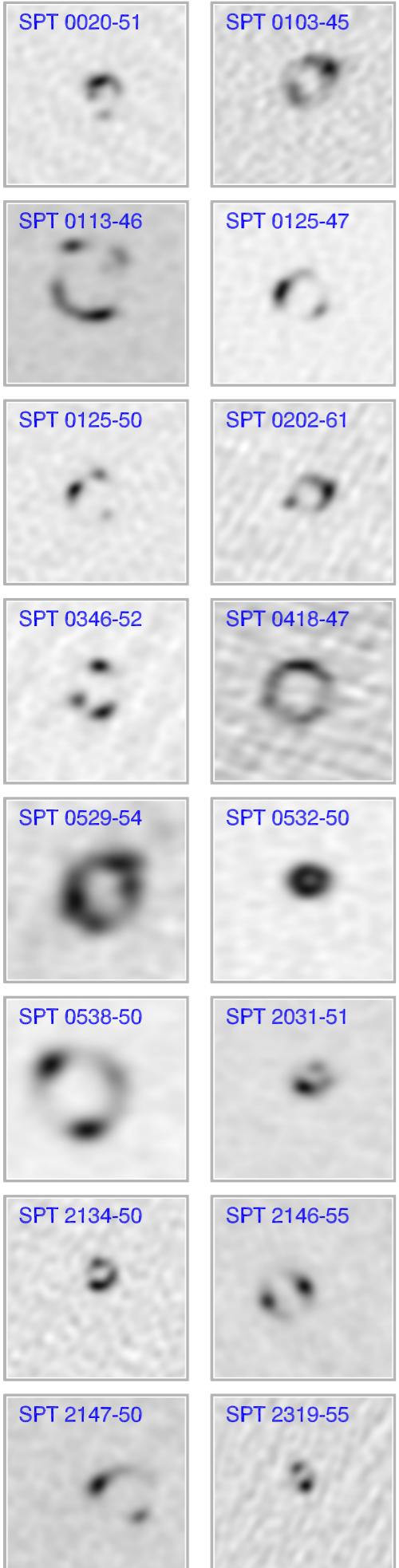
^{12}CO H_2O
 ^{13}CO H_2O^+ CI



SPT-0346-52
~30 mJy

$>10^{13} \text{ L}_\odot$
 $\text{M}_\star > 500 \text{ M}_\odot/\text{yr}$
-114 GHz





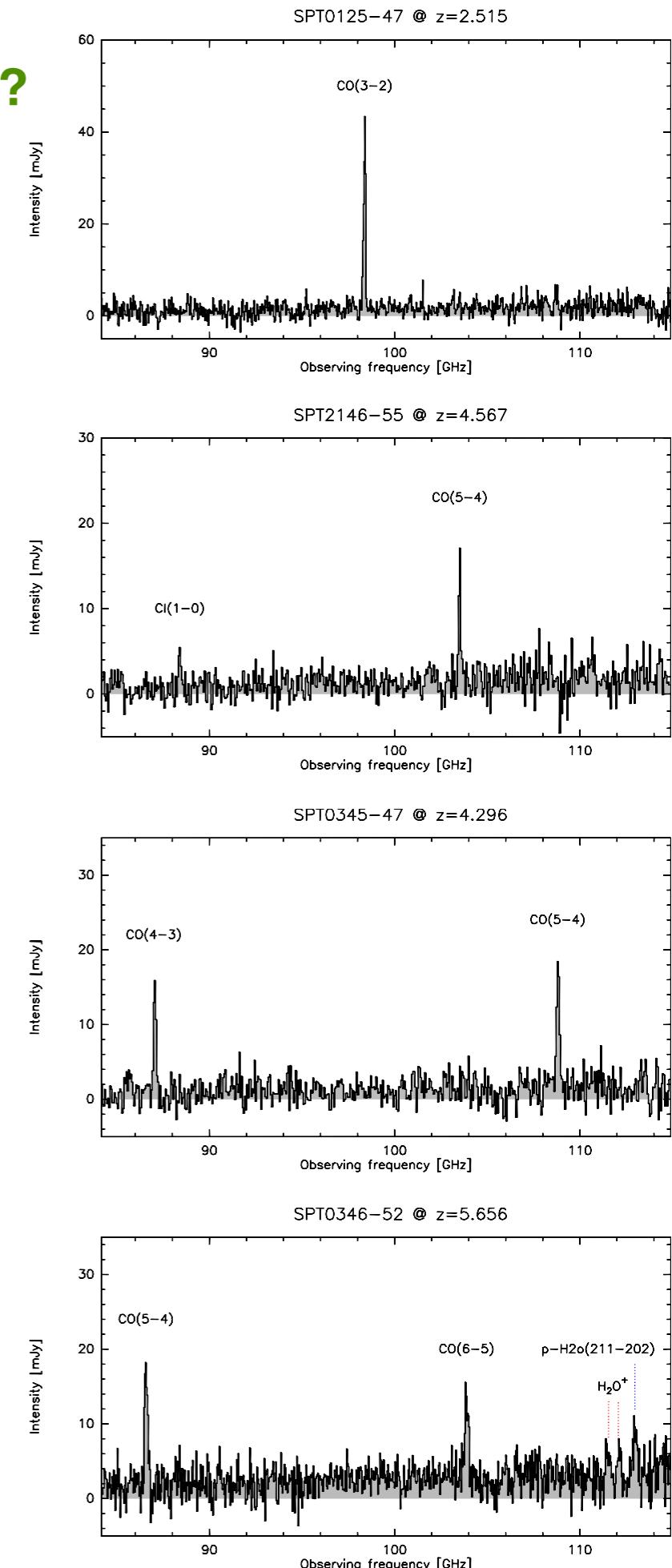
What are strongly lensed SMGs good for?

Background Source:

- Allows us to randomly sample individual sources which make up the CIB in great detail.
~ $\times 10$ brighter \Rightarrow ~ $\times 100$ less telescope time
- Lensing increases angular diameter on the sky.
 \Rightarrow We have a cosmic microscope to provide high angular resolution of the ISM at high redshift and probe kpc scales
- Detailed spectroscopy of CO, C+, H₂O (and other lines) is finally possible at high redshifts.
 \Rightarrow We can do chemistry
- The highest redshift sources provide us with a new method of probing the ISM near the end of the epoch of reionization.

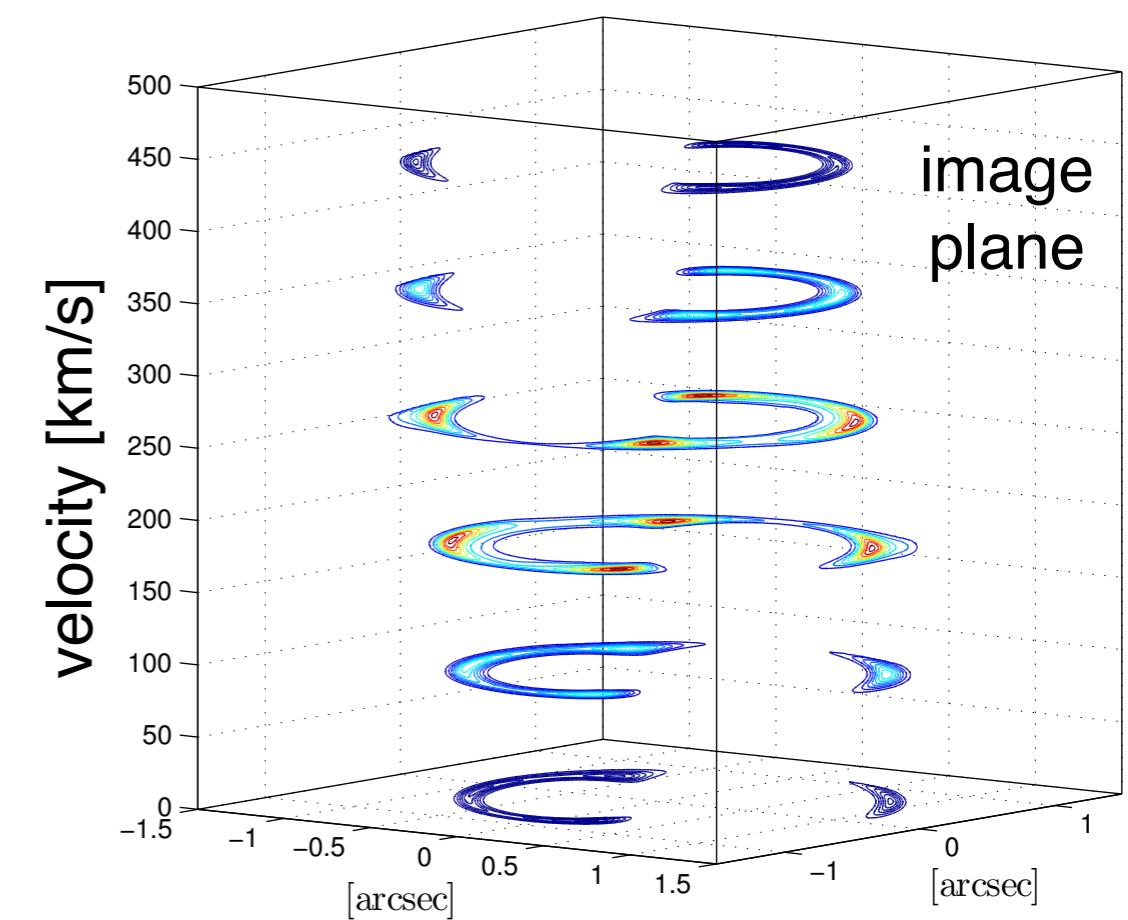
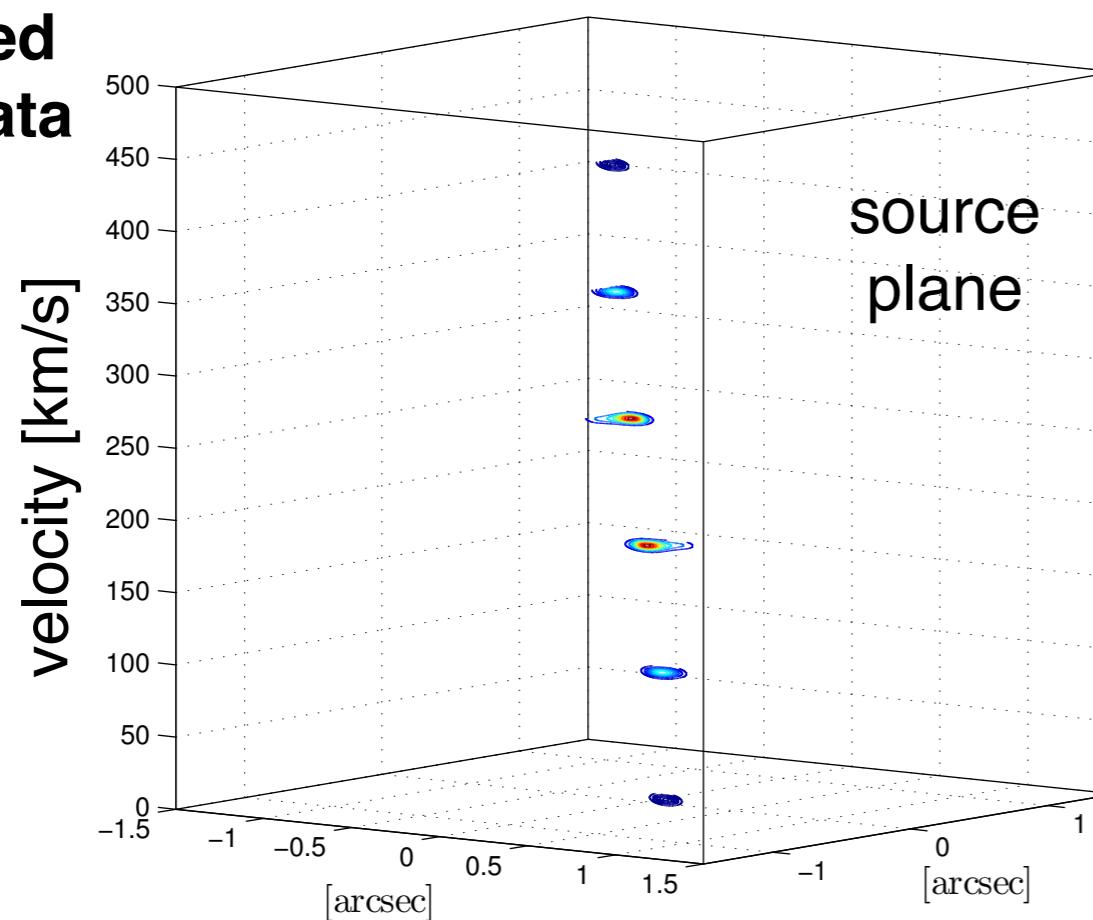
Foreground Lens:

- Study in detail the lens. \Rightarrow Study M/L ratios of massive halos out to high redshift.
- Can be used as a probe of large scale structure \Rightarrow may one day be used for cosmology
- direct probe of DM (sub) structure in the lensing halos

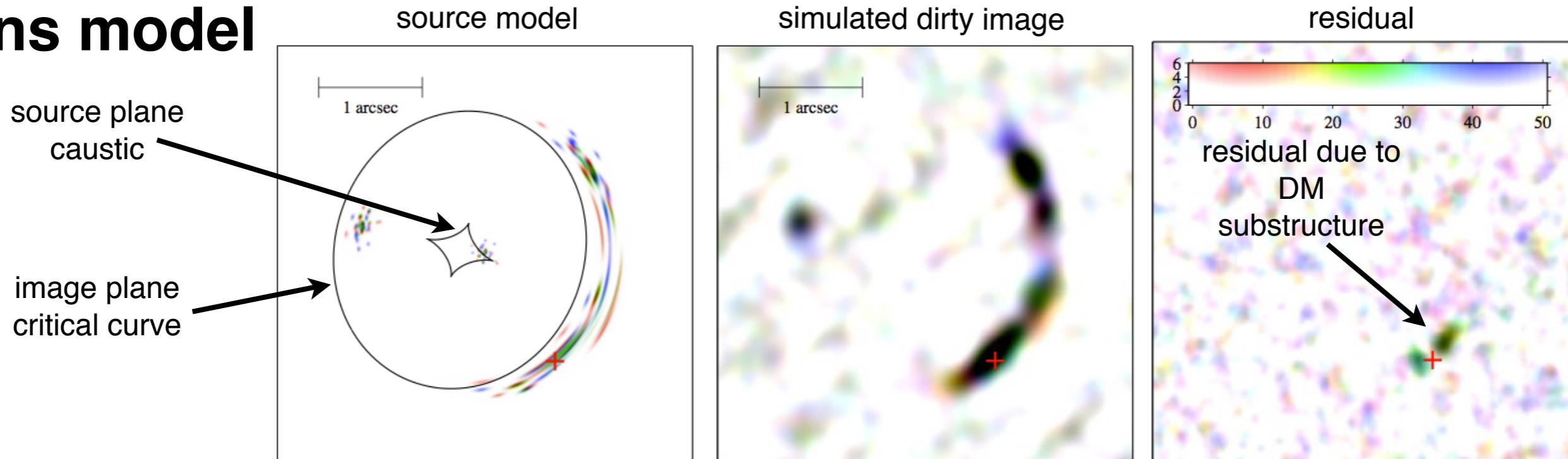


Detecting dark matter substructure at $z \sim 1$

simulated
ALMA data
cube

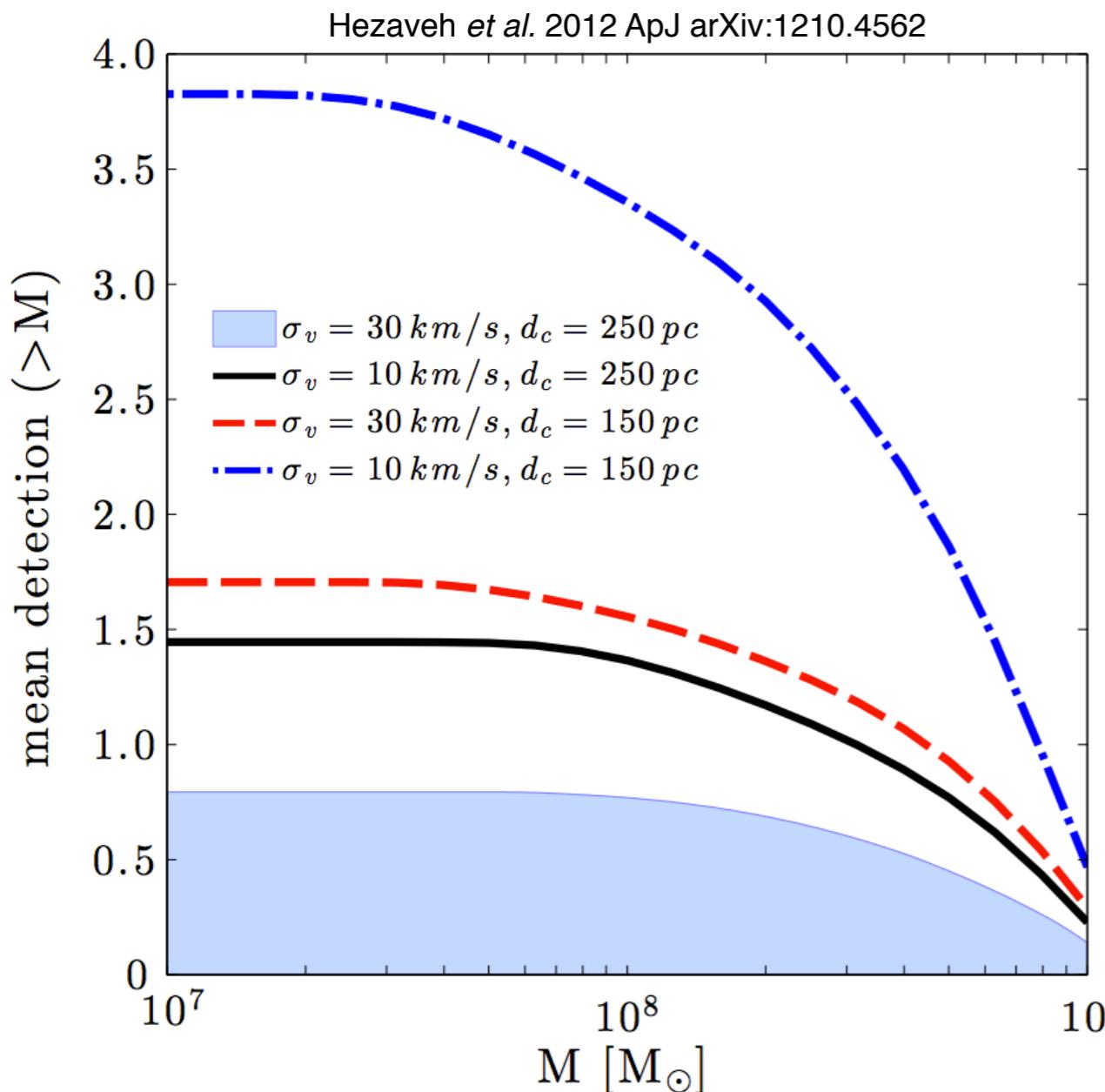


lens model

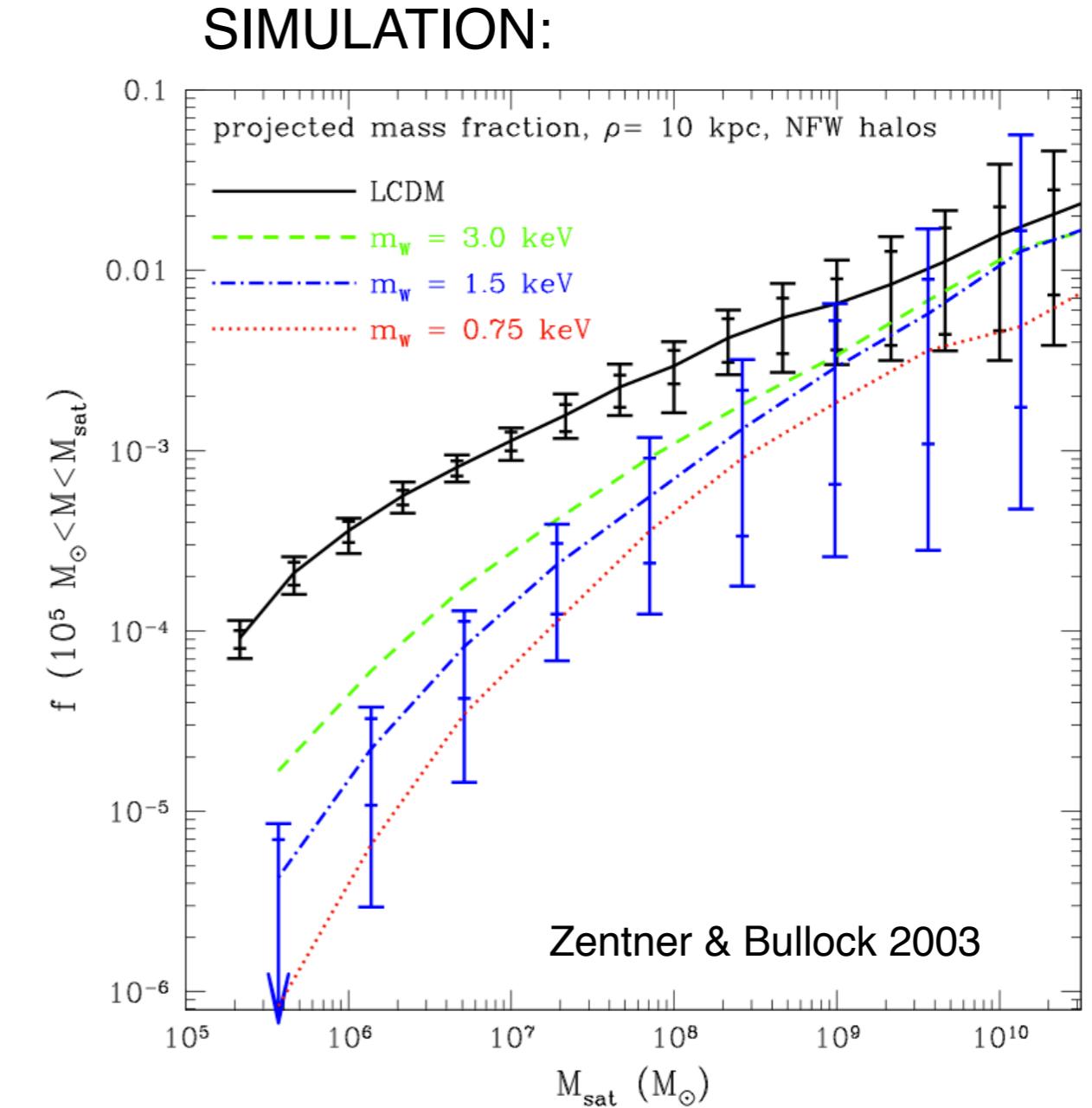


Detecting dark matter substructure at z~1

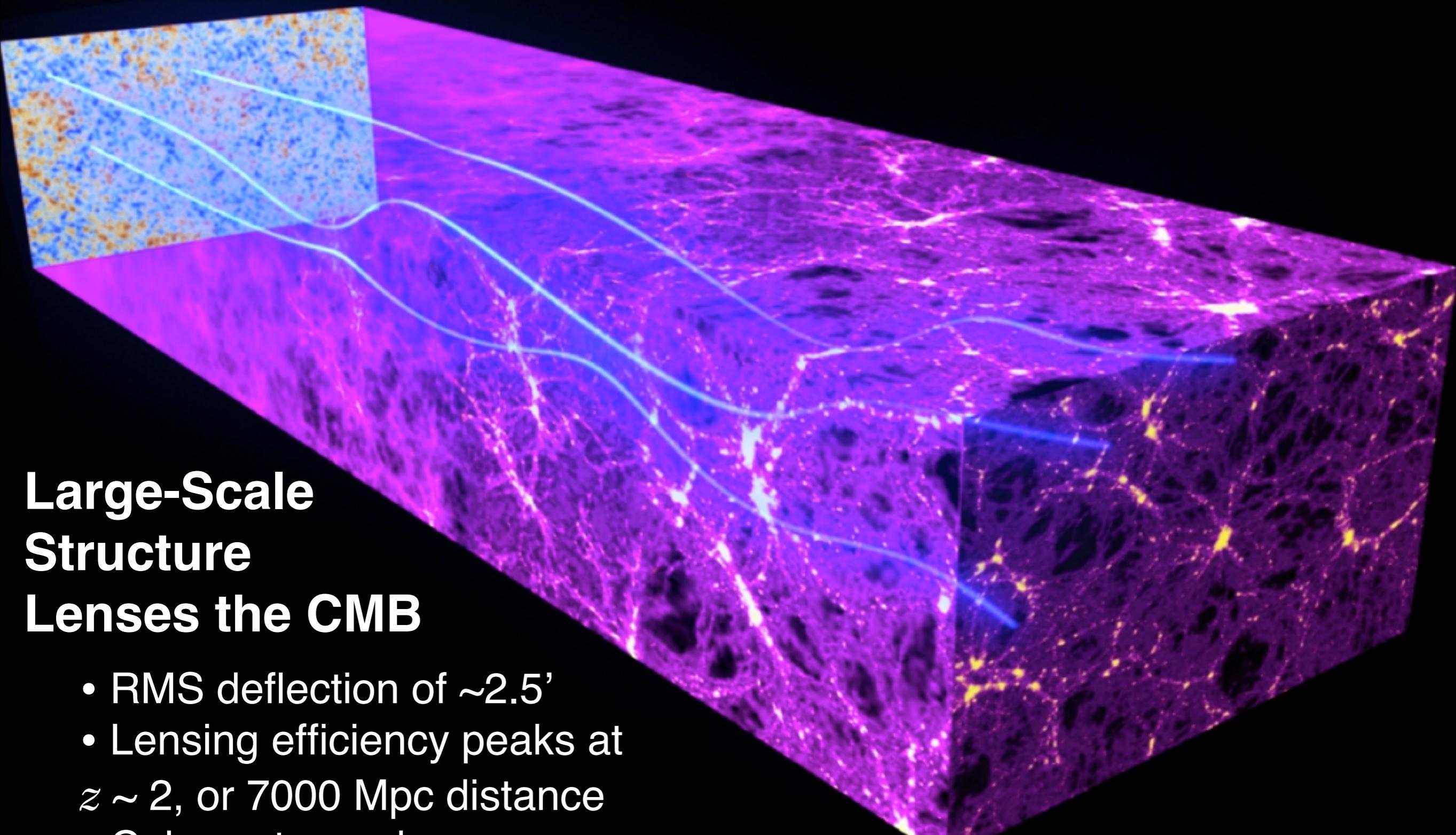
What will it tell us?



We will detect ~ 1 $M_{\text{sat}} > 10^8 M_{\odot}$ dark matter subhalo per lensed system with about 1 hour per source with ALMA



We can constrain models of DM, in particular, prove or disprove the existence of warm DM

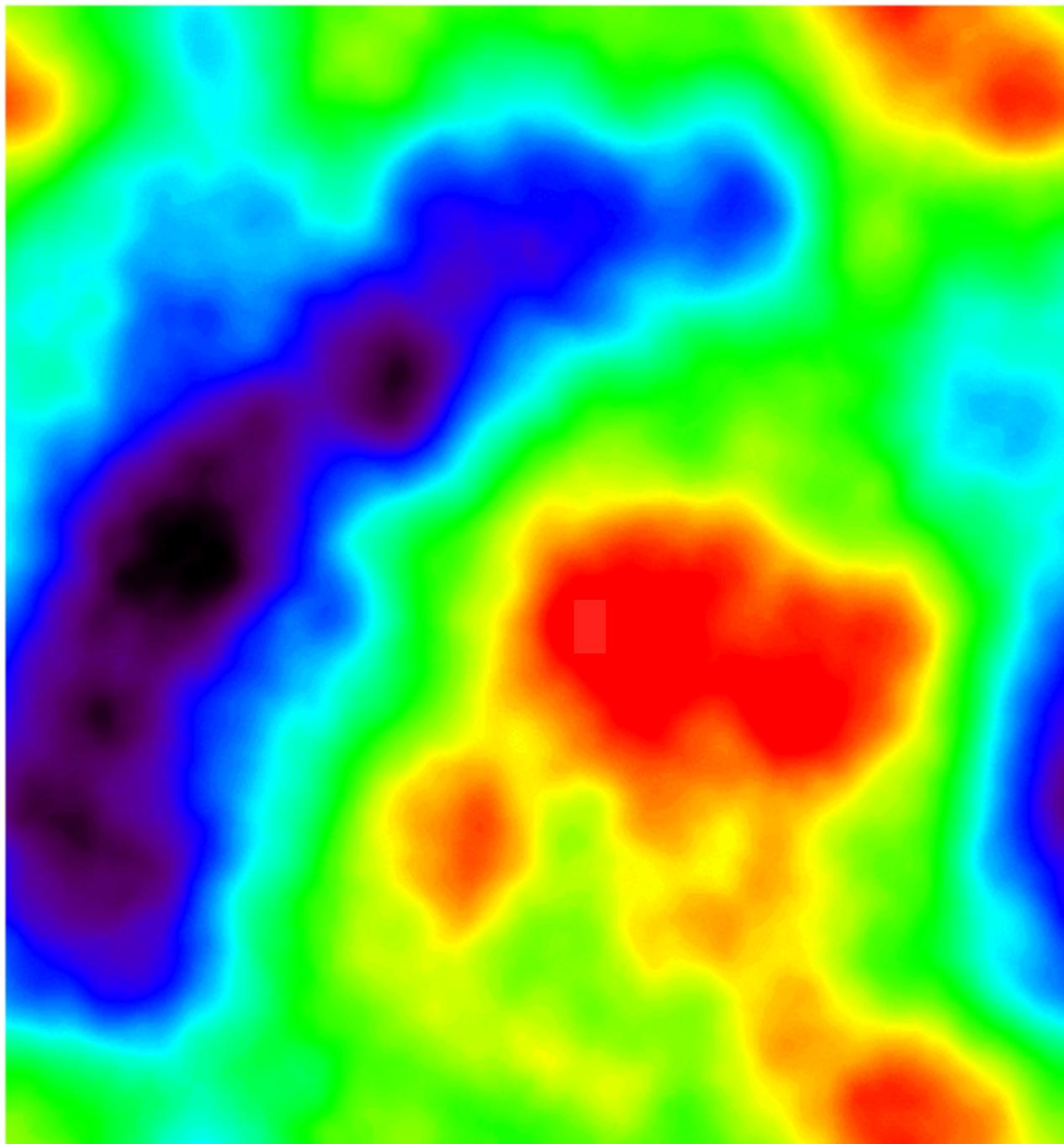


Large-Scale Structure Lenses the CMB

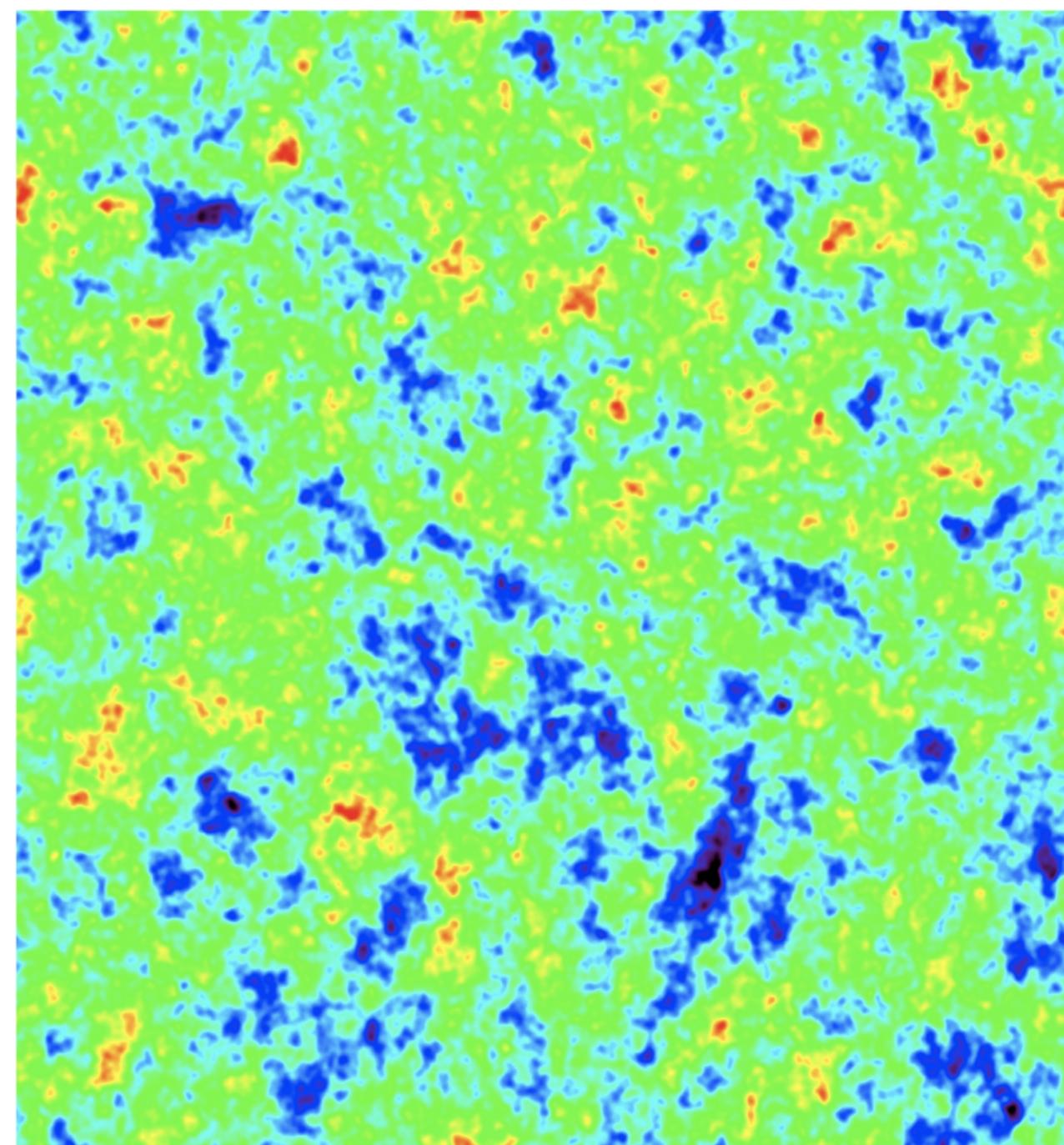
- RMS deflection of $\sim 2.5'$
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on \sim degree (~ 300 Mpc) scales

Lensing of the CMB

17°x17°



lensing potential

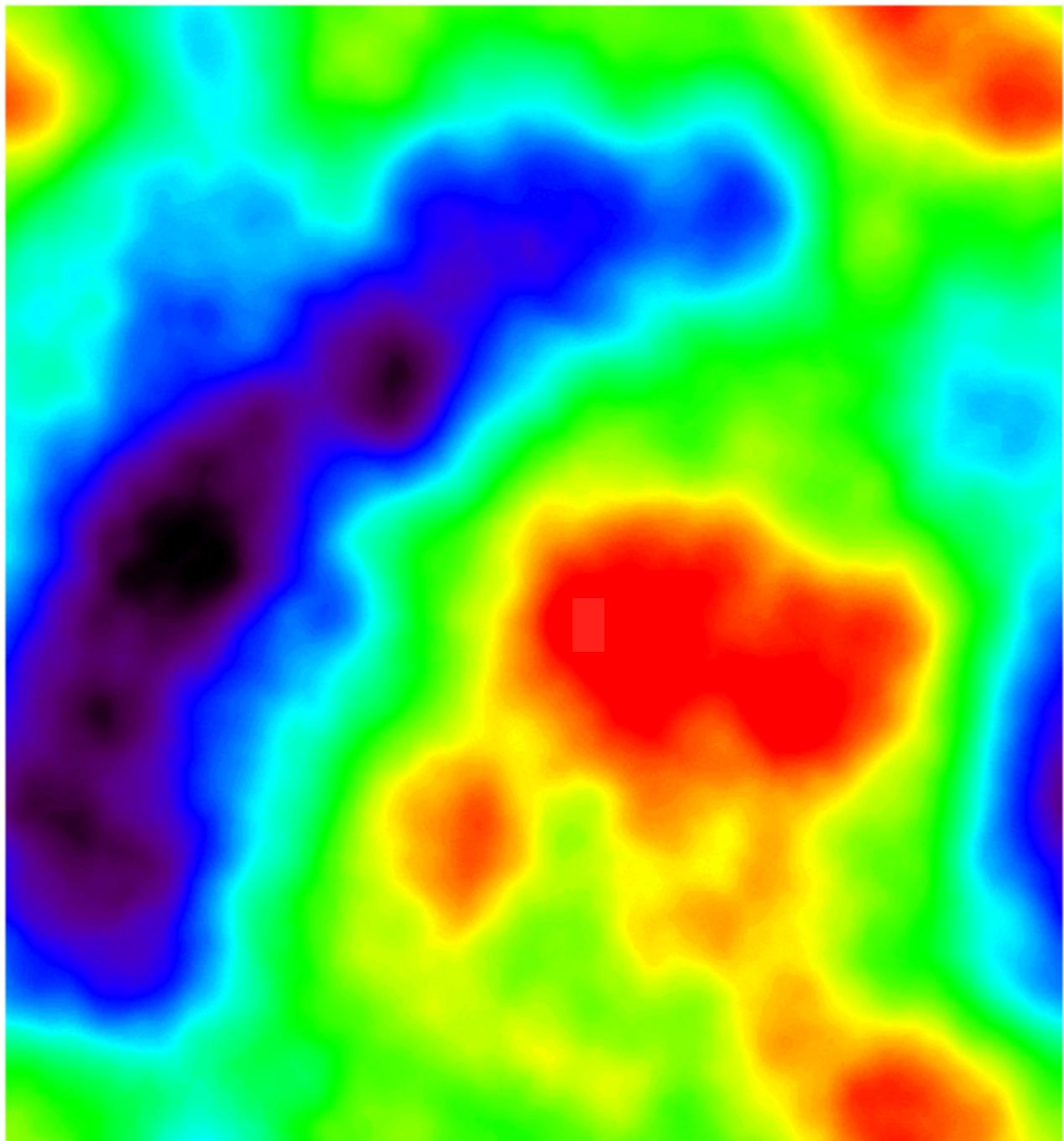


unlensed cmb

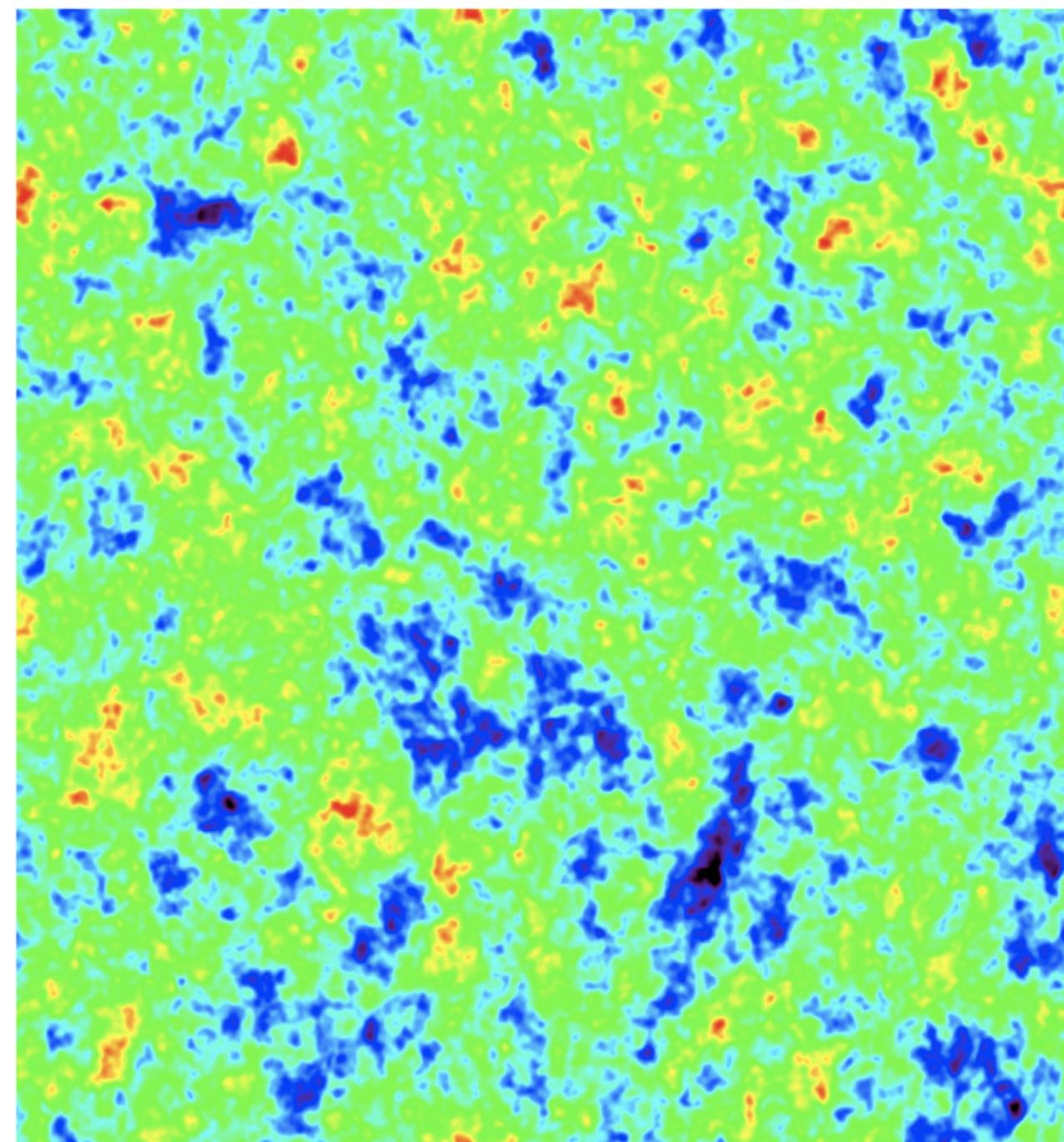
from Alex van Engelen

Lensing of the CMB

17°x17°



lensing potential

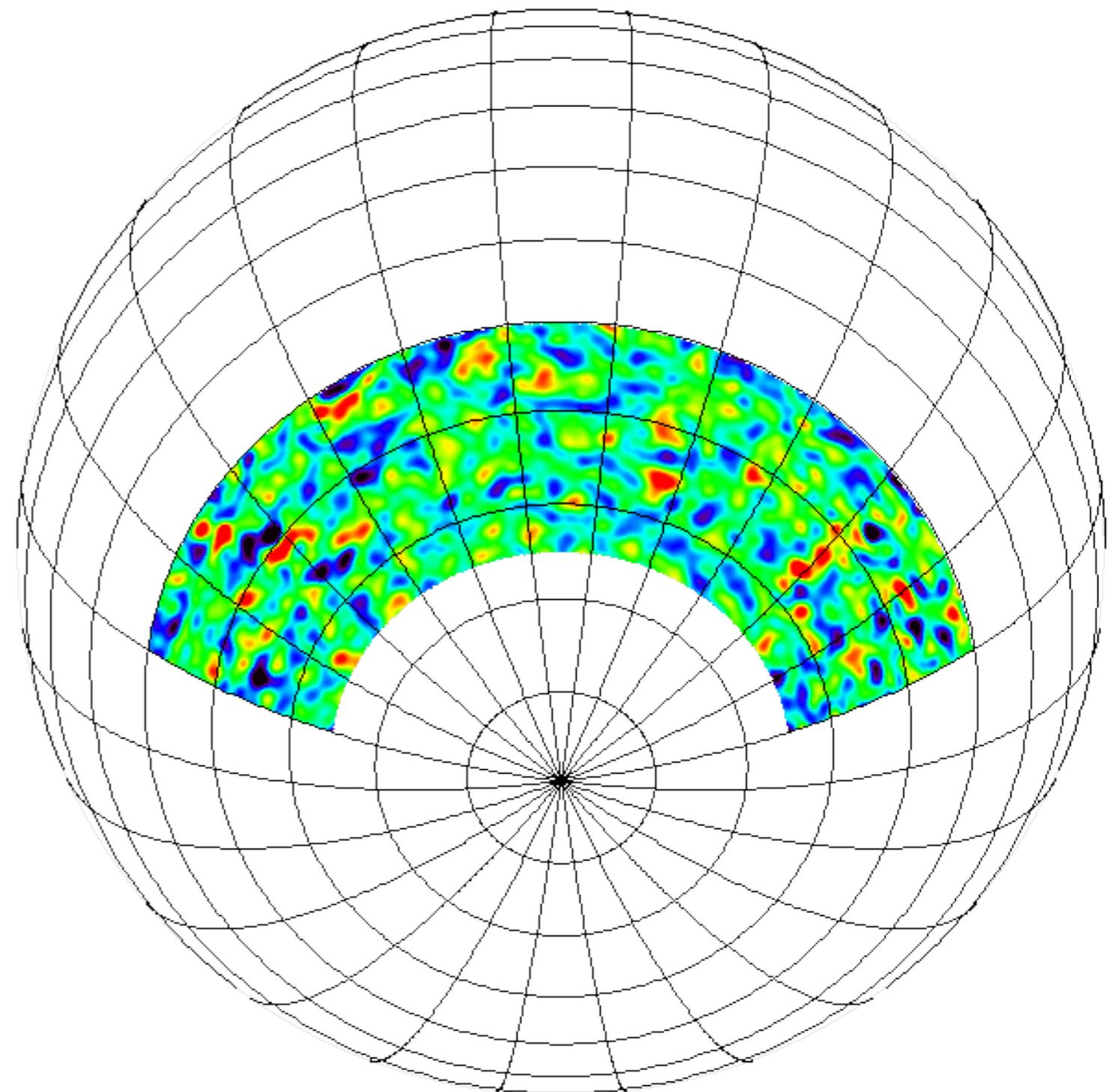


lensed cmb

from Alex van Engelen

Gravitational Lensing of the CMB

- The CMB damping tail is sensitive to structure along the line of sight through gravitational lensing
- The CMB lensing redshift kernel peaks at $1 < z < 3$
- Basically gives a measure of σ_8 at $z \sim 2$
- SPT has produced a map of the line-of-sight mean density with $S/N \sim 1$ per square degree
- This can be cross correlated with catalogs of galaxies to directly measure the bias or mean halo mass in which the objects reside

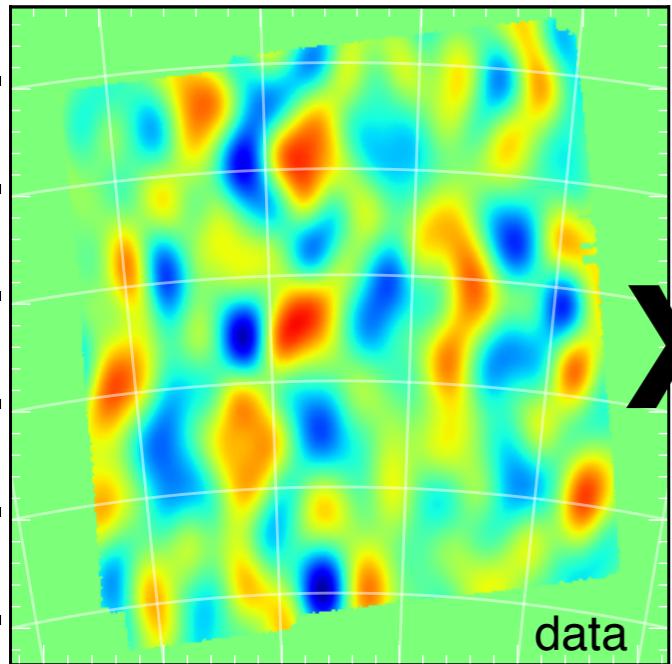


Van Engelen et al. 2012 ApJ
Bleem et al. 2012 ApJ

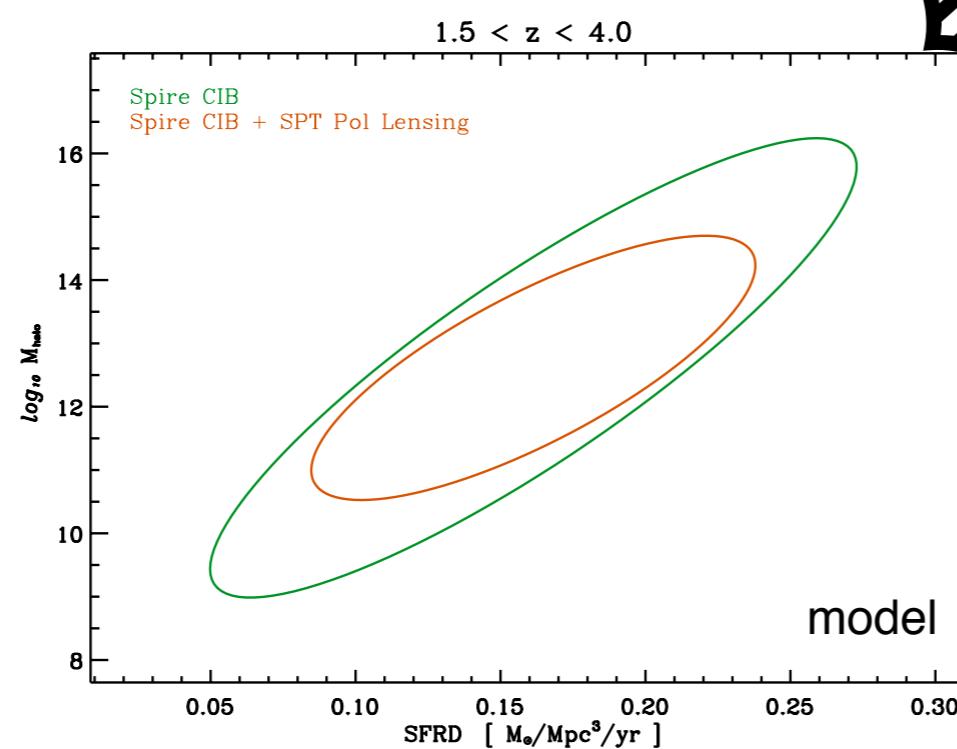
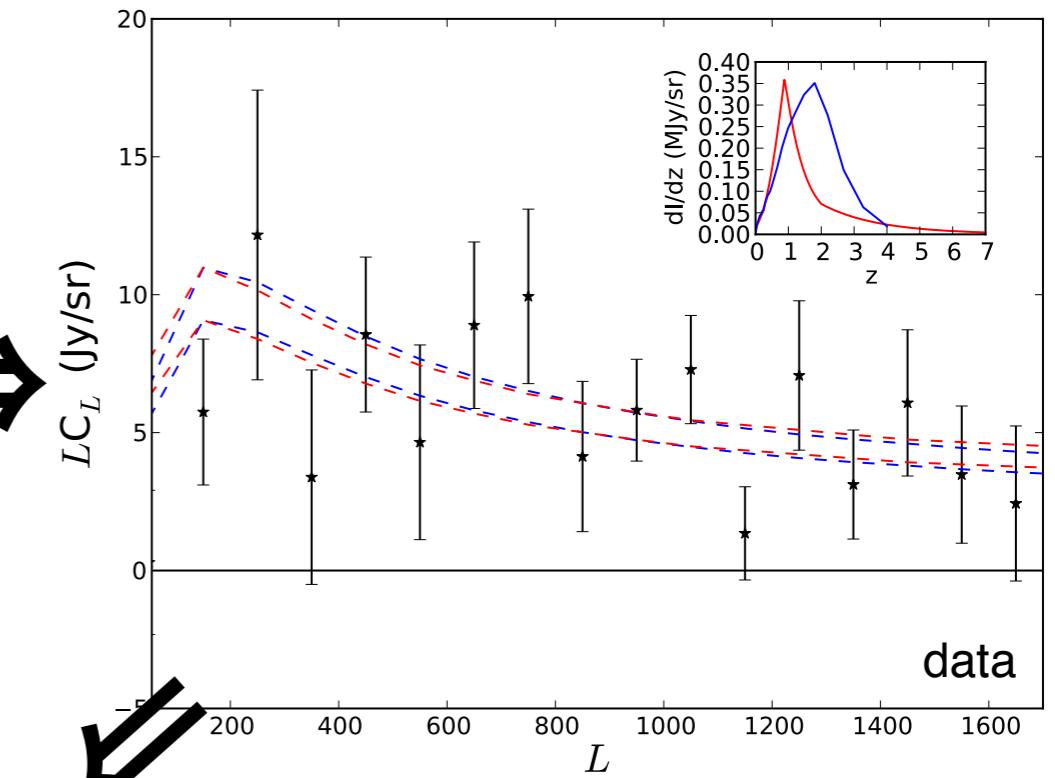
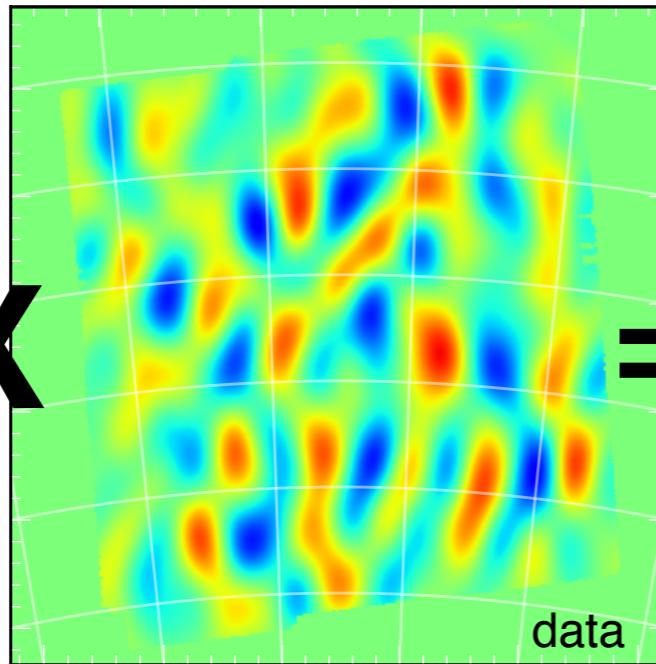
Weighing the CIB with CMB lensing maps

Holder et al. 2013

SPT CMB lensing map



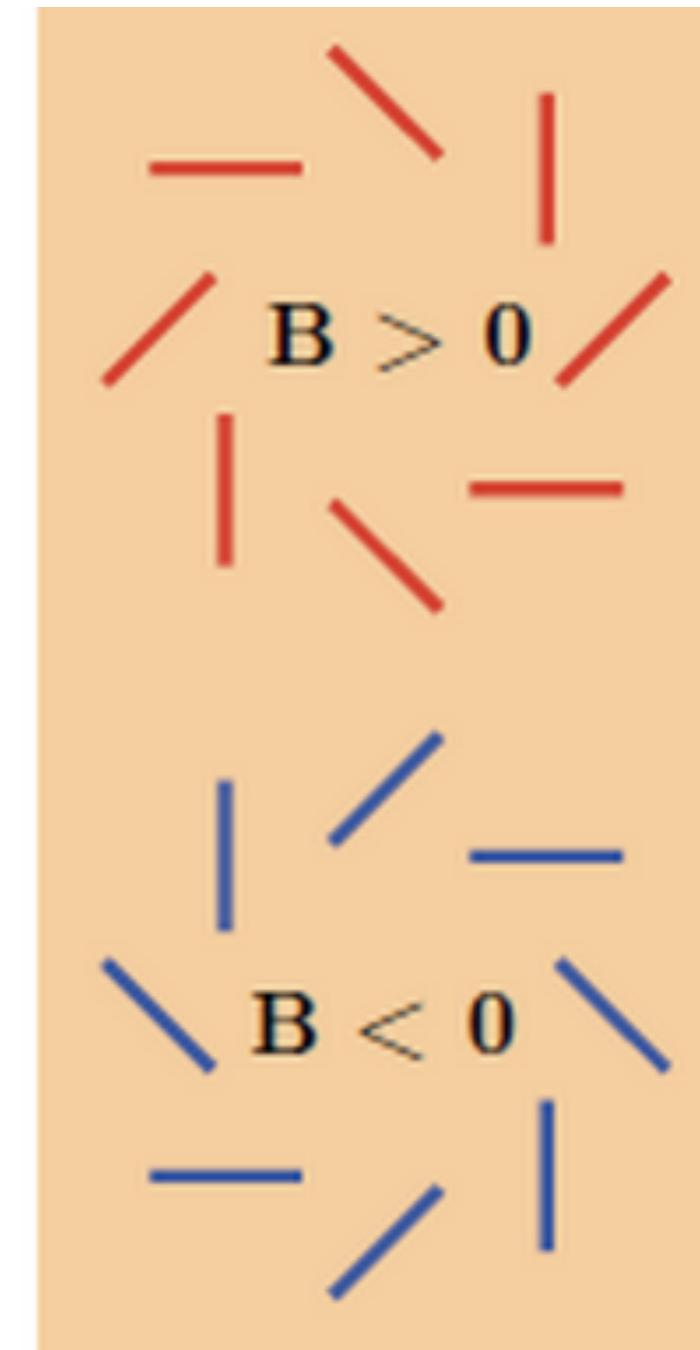
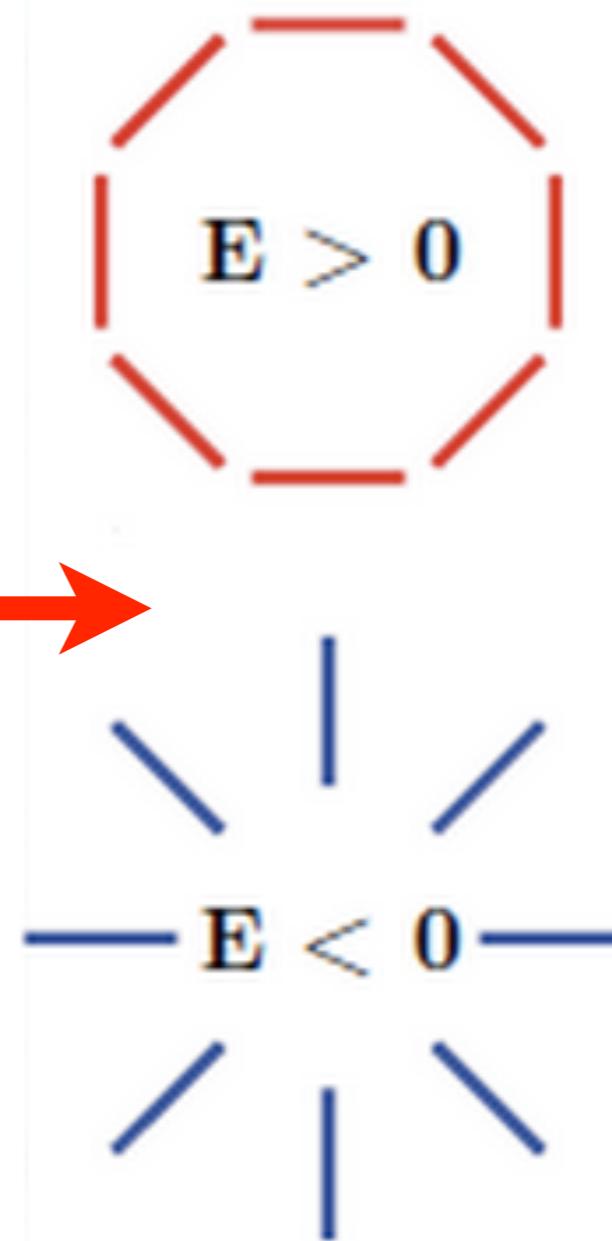
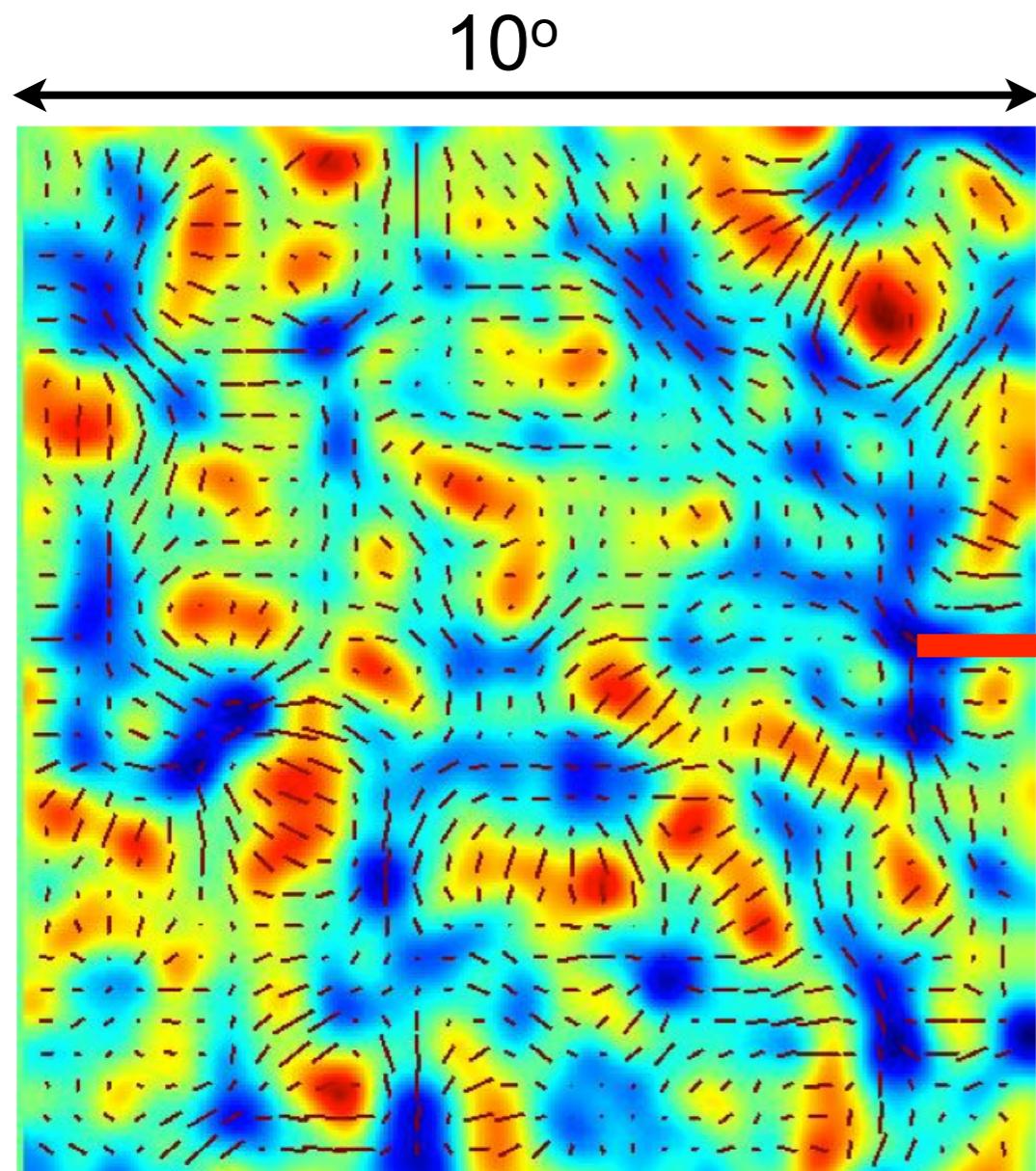
Herschel/SPIRE 500 μm
CIB density map



10 σ detection of bias
 $b=2.0+/-0.2$
 $\sim 10^{13} M_{\odot}$ halos at $z\sim 2$

Provides a measure of the specific star formation rate.

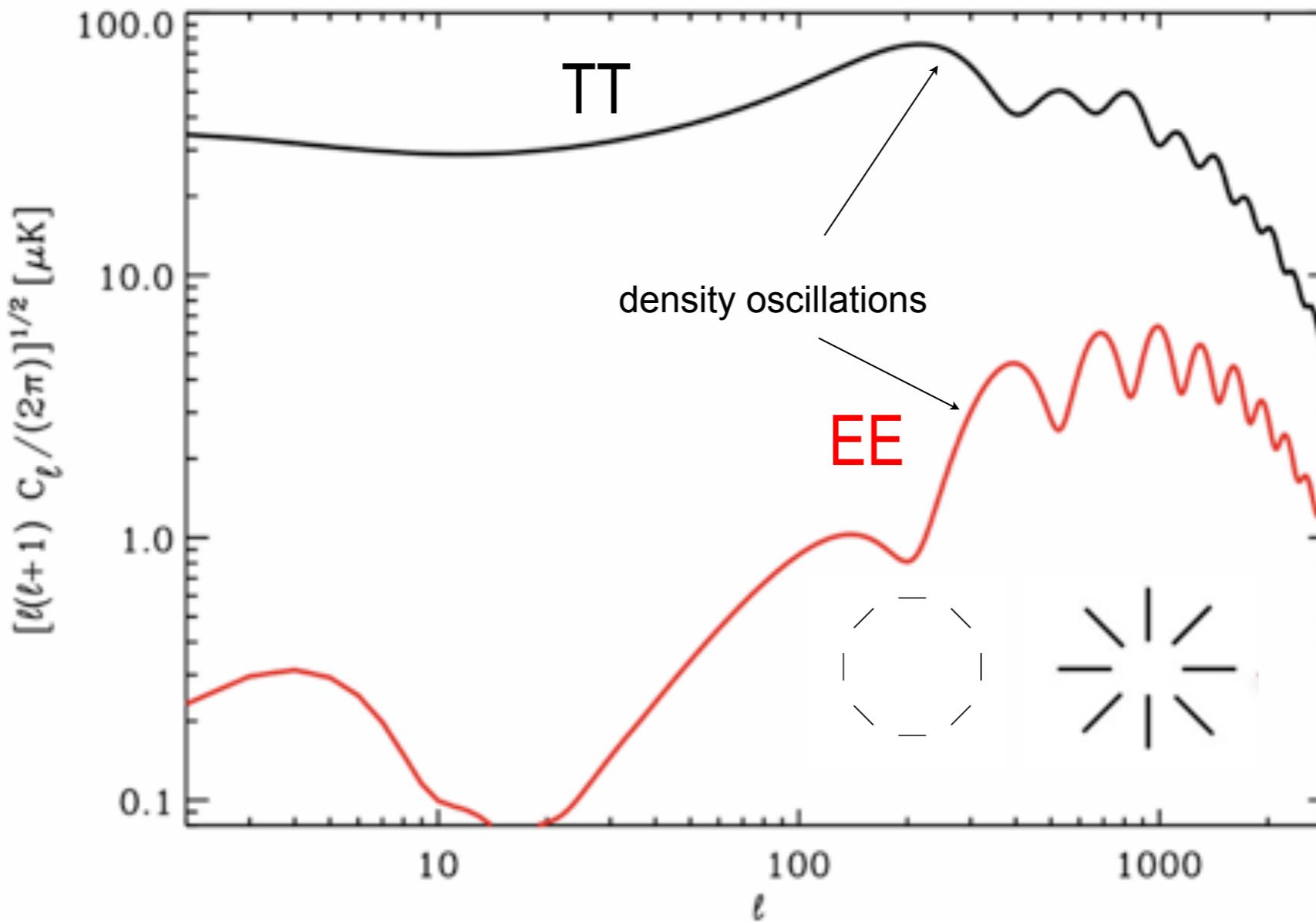
The Next Frontier: The Polarization of the CMB



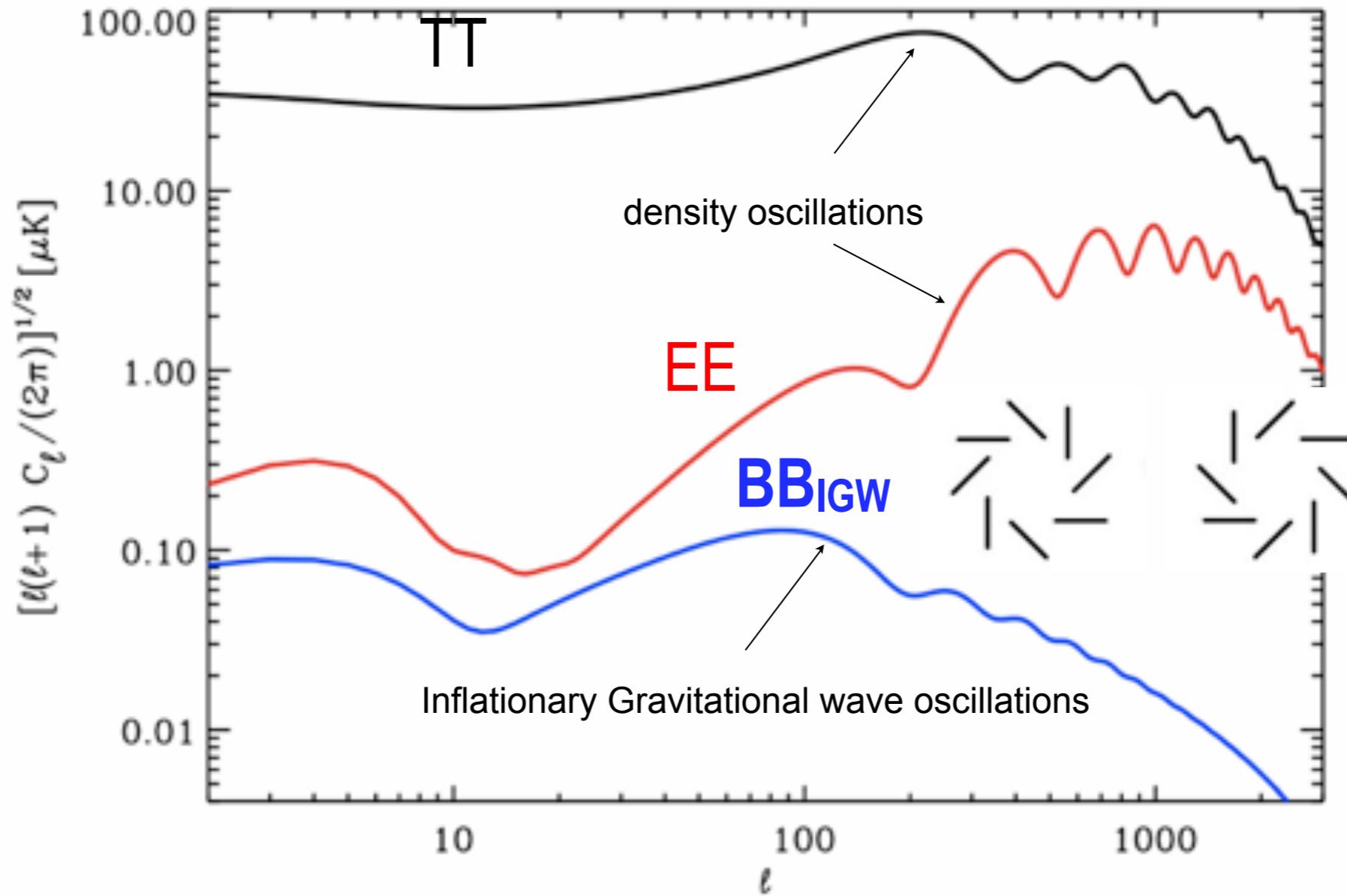
E-modes:
Even Parity

B-modes:
Odd Parity

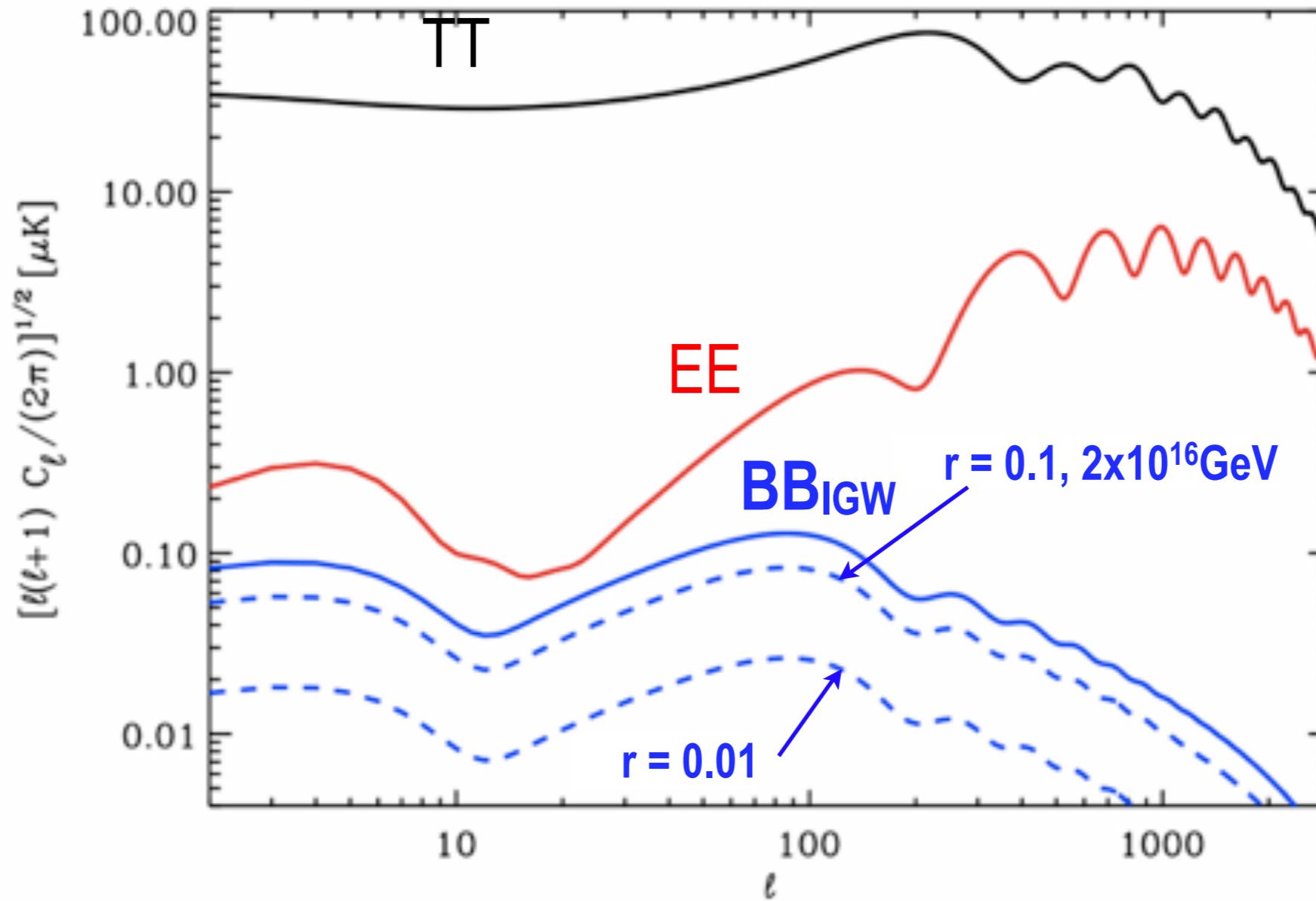
CMB polarization: the next frontier for lensing & inflation



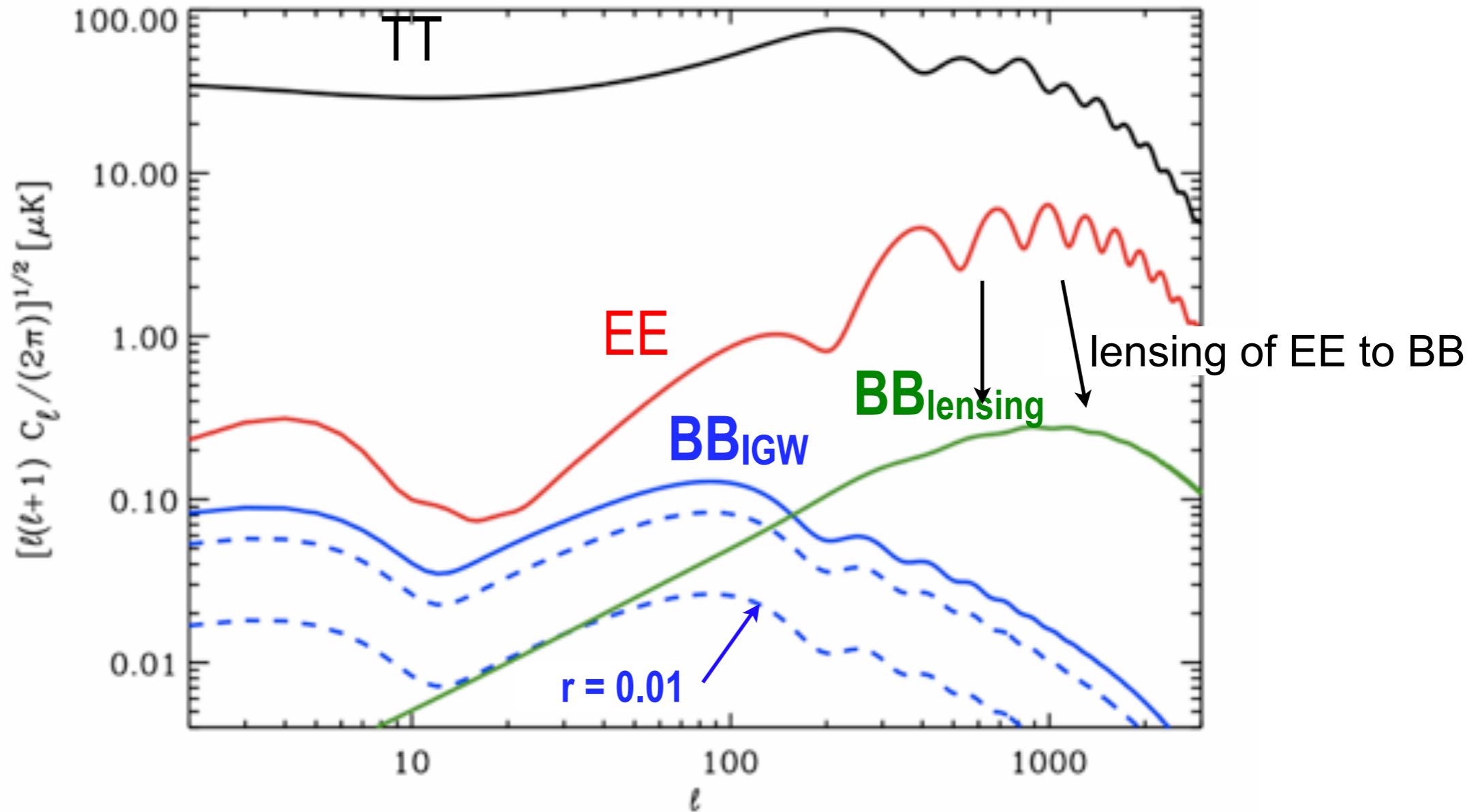
CMB polarization: the next frontier for lensing & inflation



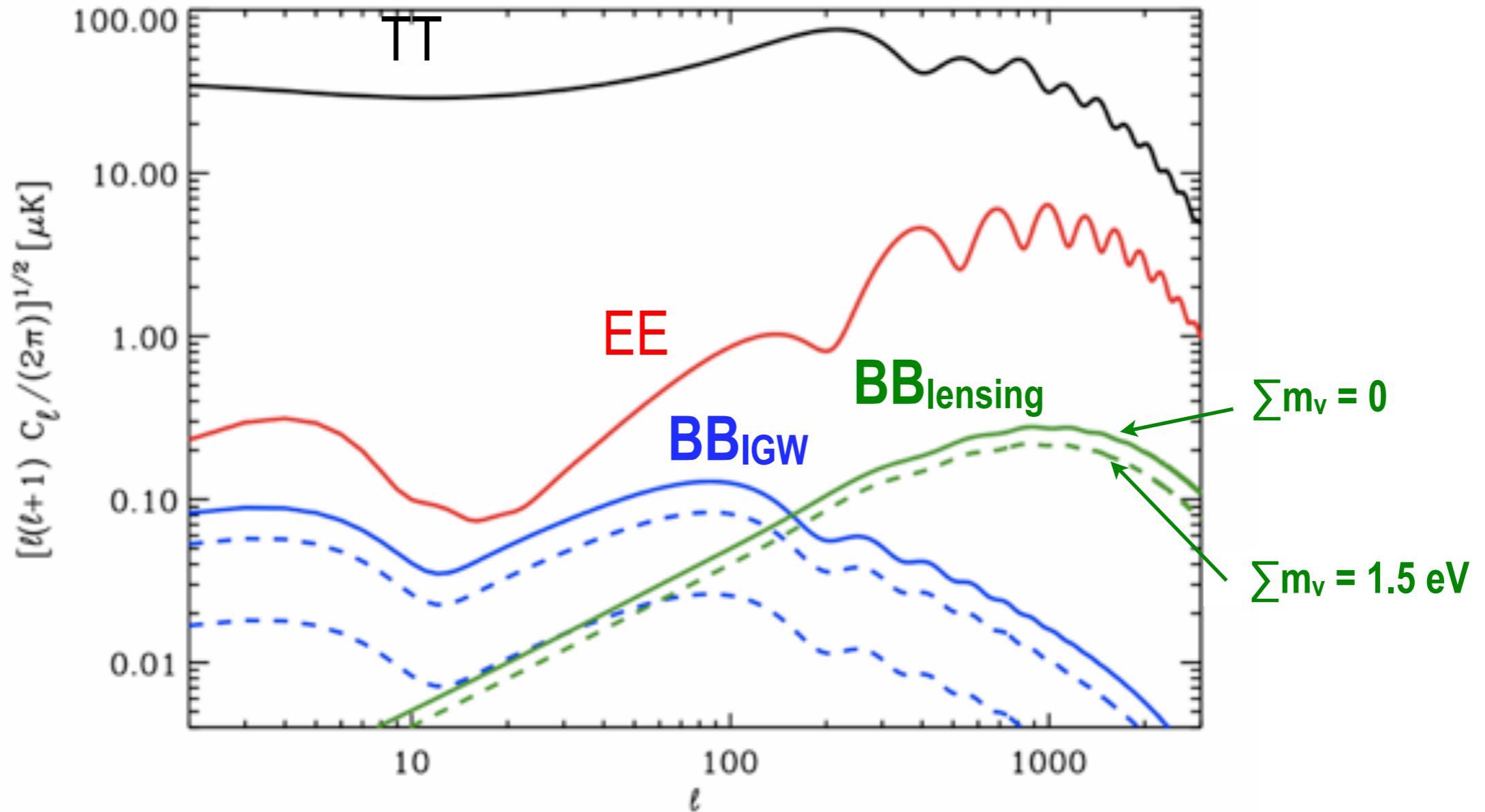
CMB polarization: the next frontier for lensing & inflation



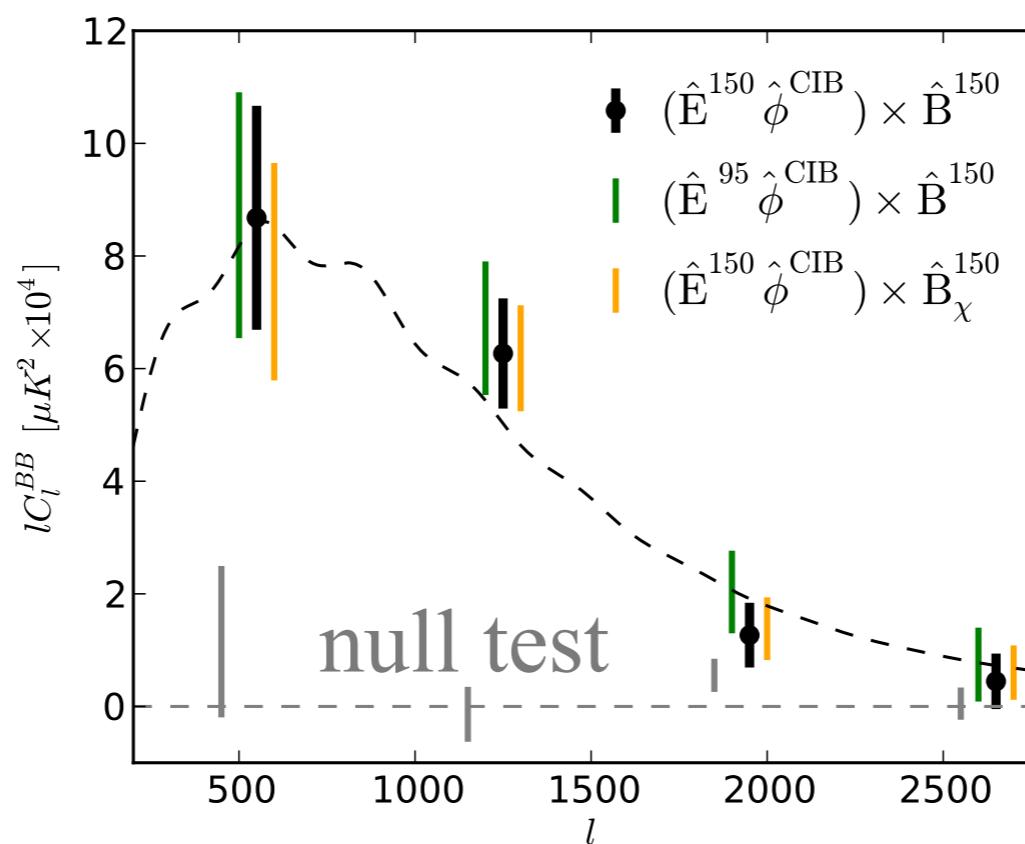
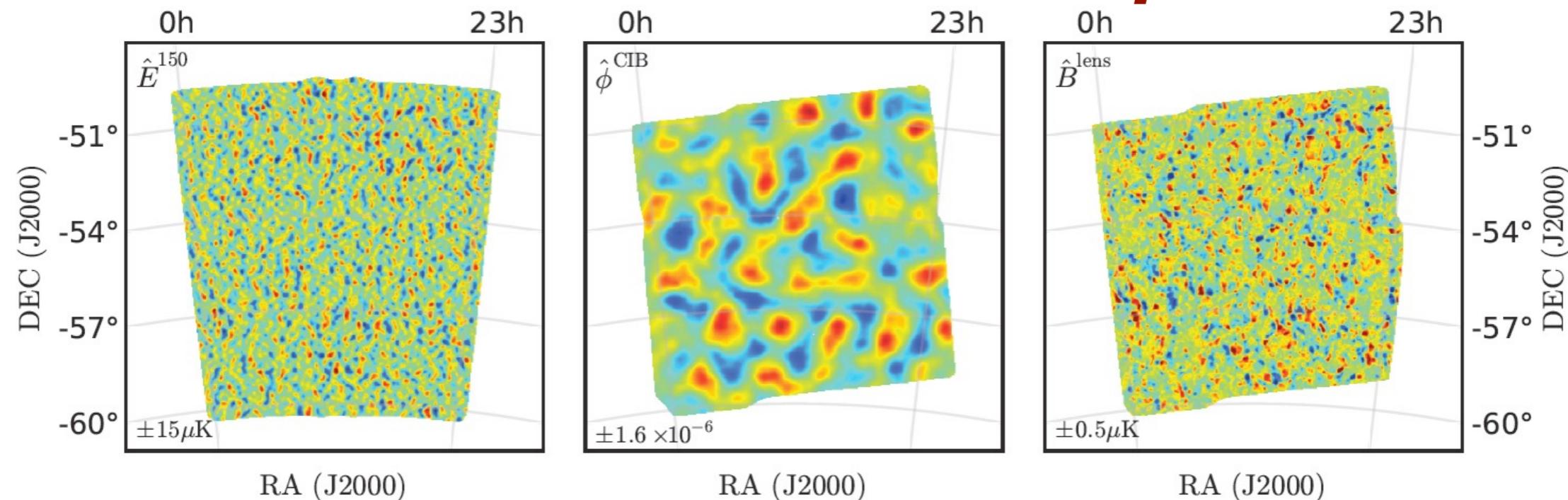
CMB polarization: the next frontier for lensing & inflation



CMB polarization: the next frontier for lensing & inflation



Detection of B-mode Polarization in the CMB with Data from SPTpol



**7.7- σ detection
of lensing B-
modes!**

Current state of CMB polarization measurements

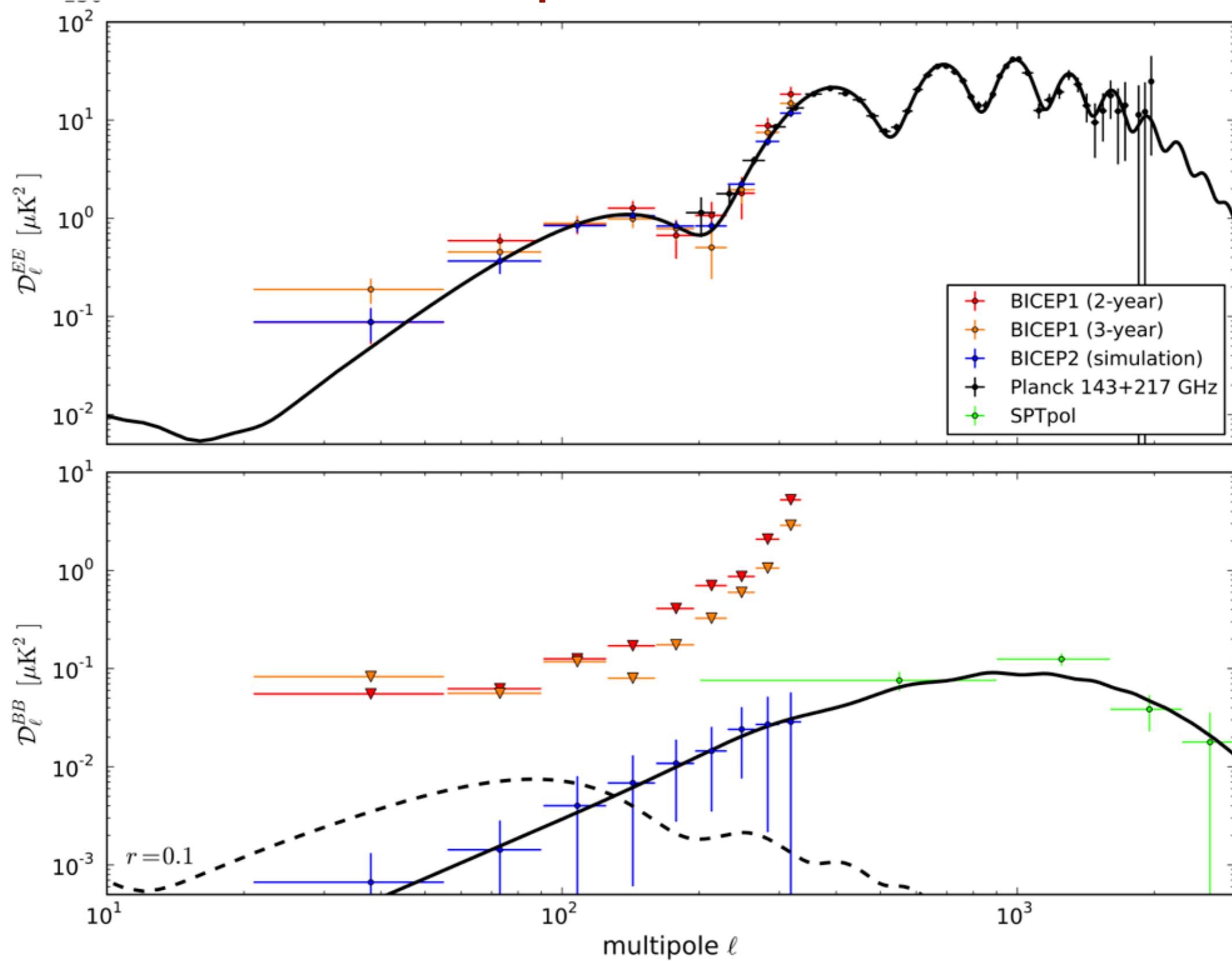


Figure courtesy of Grant Teply, Caltech grad student

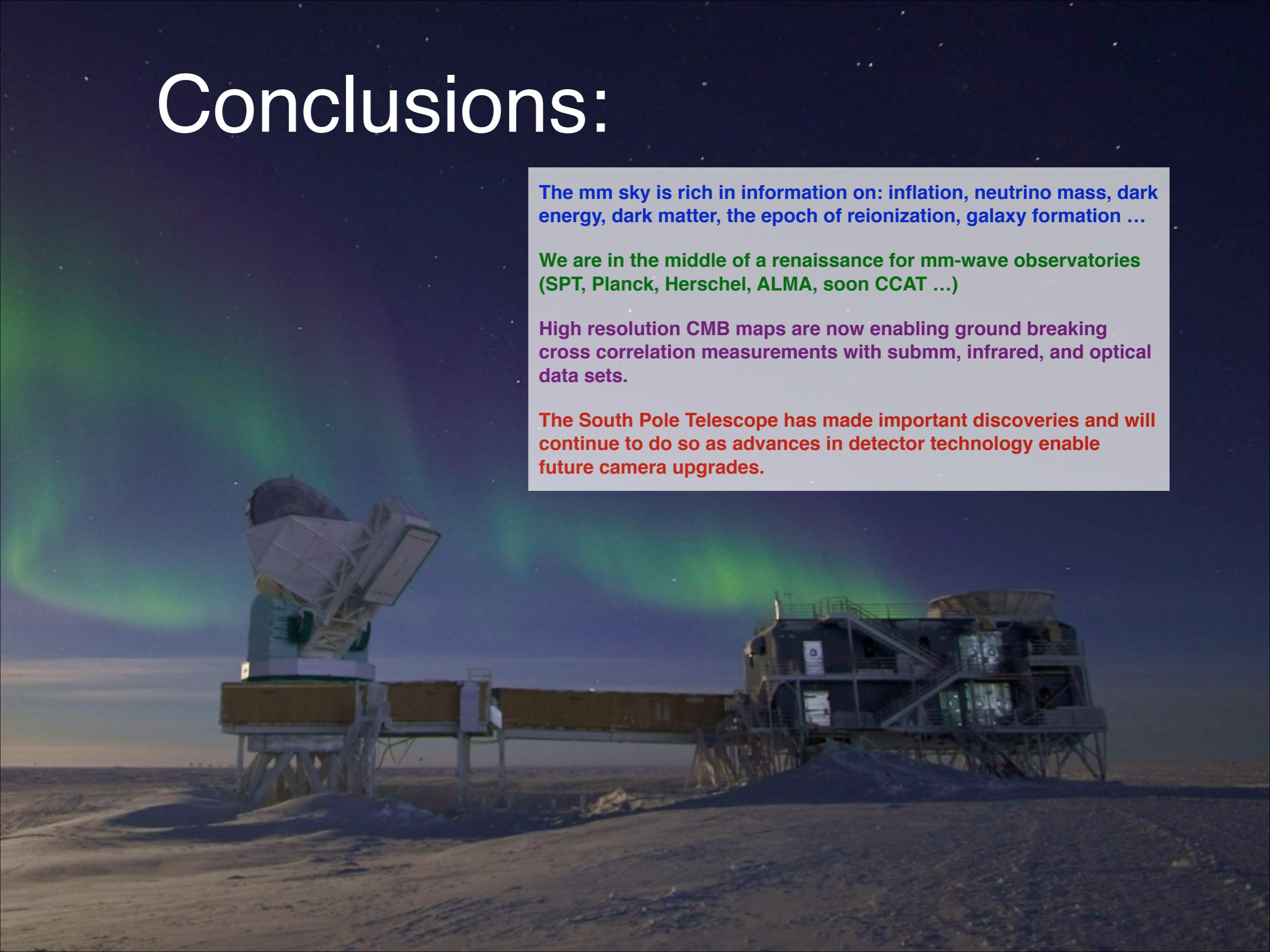
Conclusions:

The mm sky is rich in information on: inflation, neutrino mass, dark energy, dark matter, the epoch of reionization, galaxy formation ...

We are in the middle of a renaissance for mm-wave observatories (SPT, Planck, Herschel, ALMA, soon CCAT ...)

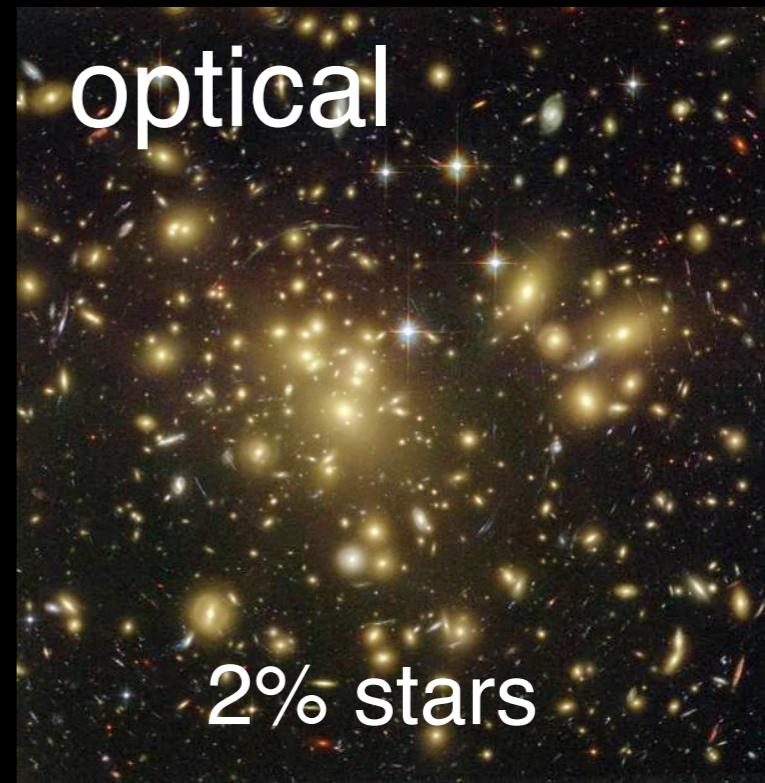
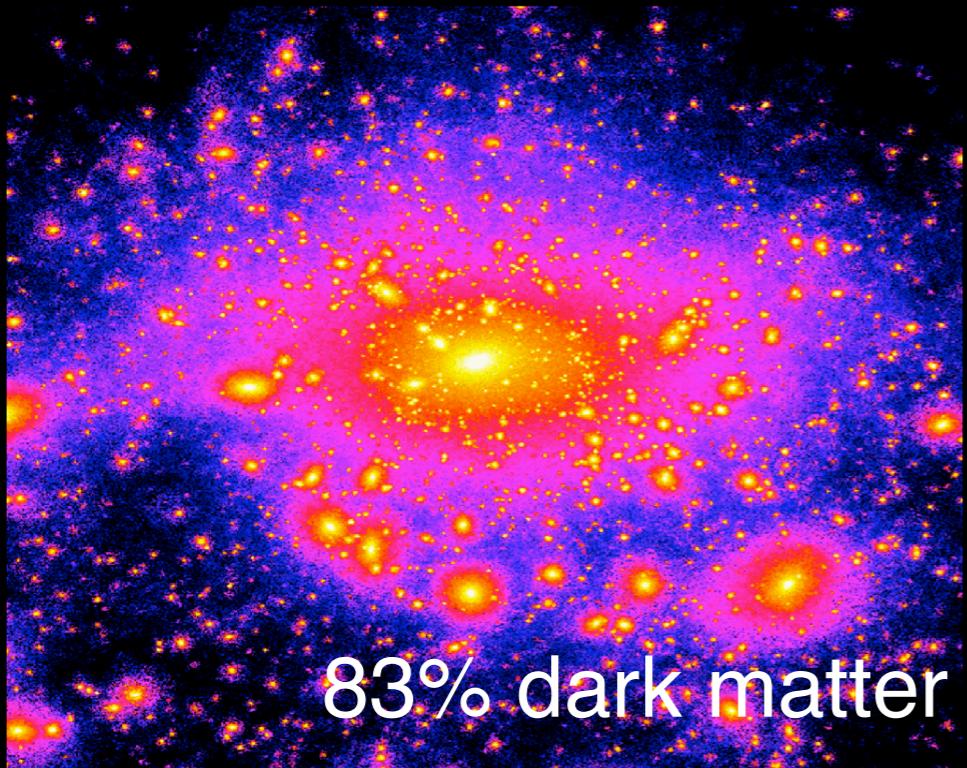
High resolution CMB maps are now enabling ground breaking cross correlation measurements with submm, infrared, and optical data sets.

The South Pole Telescope has made important discoveries and will continue to do so as advances in detector technology enable future camera upgrades.



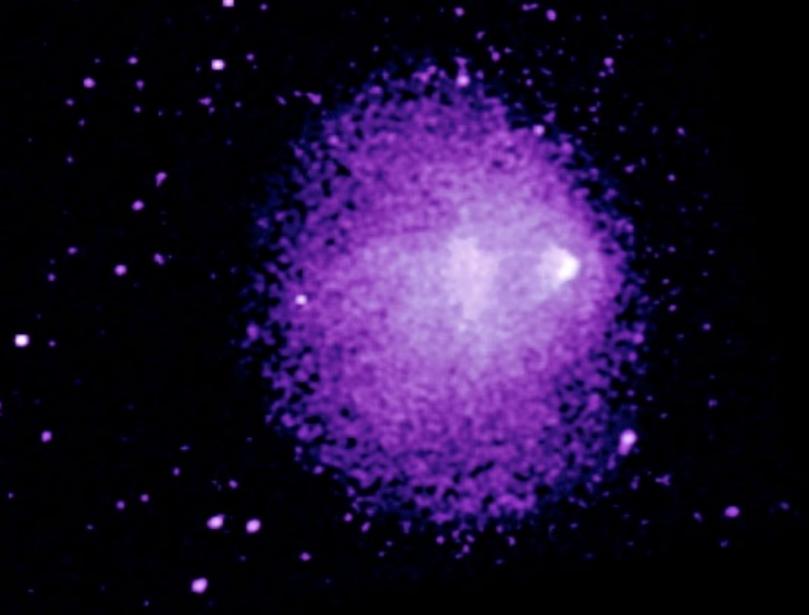
The background of the image is a dense field of stars of various colors and brightness, centered around a bright yellow-orange cluster. The word "FIN" is overlaid in large, white, sans-serif capital letters.

FIN



Constituents of a Galaxy Cluster

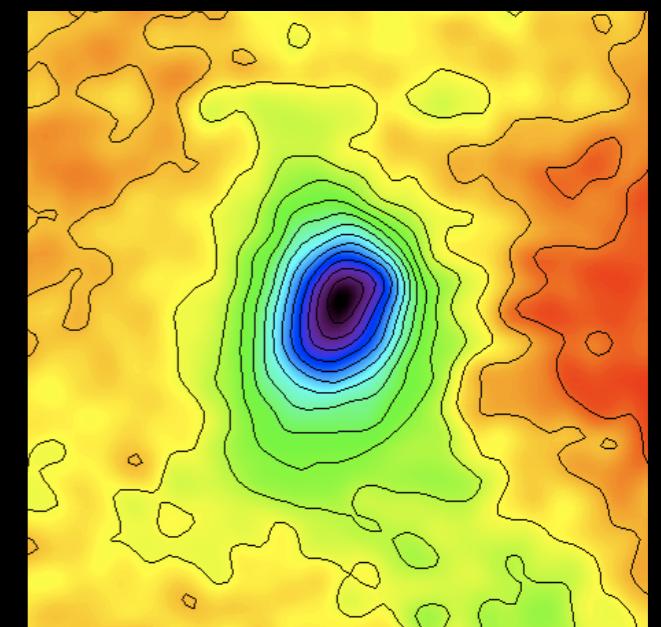
Chandra (x-ray)



15% hot gas (ICM)

$T \sim 10^7 - 10^8 \text{ K}$

SPT (SZ)



The Future with CCAT

- 25m telescope at a great site will make submm astronomy object-oriented
- Beam size will allow us to get optical redshifts directly → no need for intermediate followup.
- Extragalactic Instrument Suite:
 - 350 μm camera (Cornell/JPL)
 - 0.85/1.1/1.4/2.0mm camera (Caltech/JPL)
 - X-Spec 1mm spectrometer (JPL)

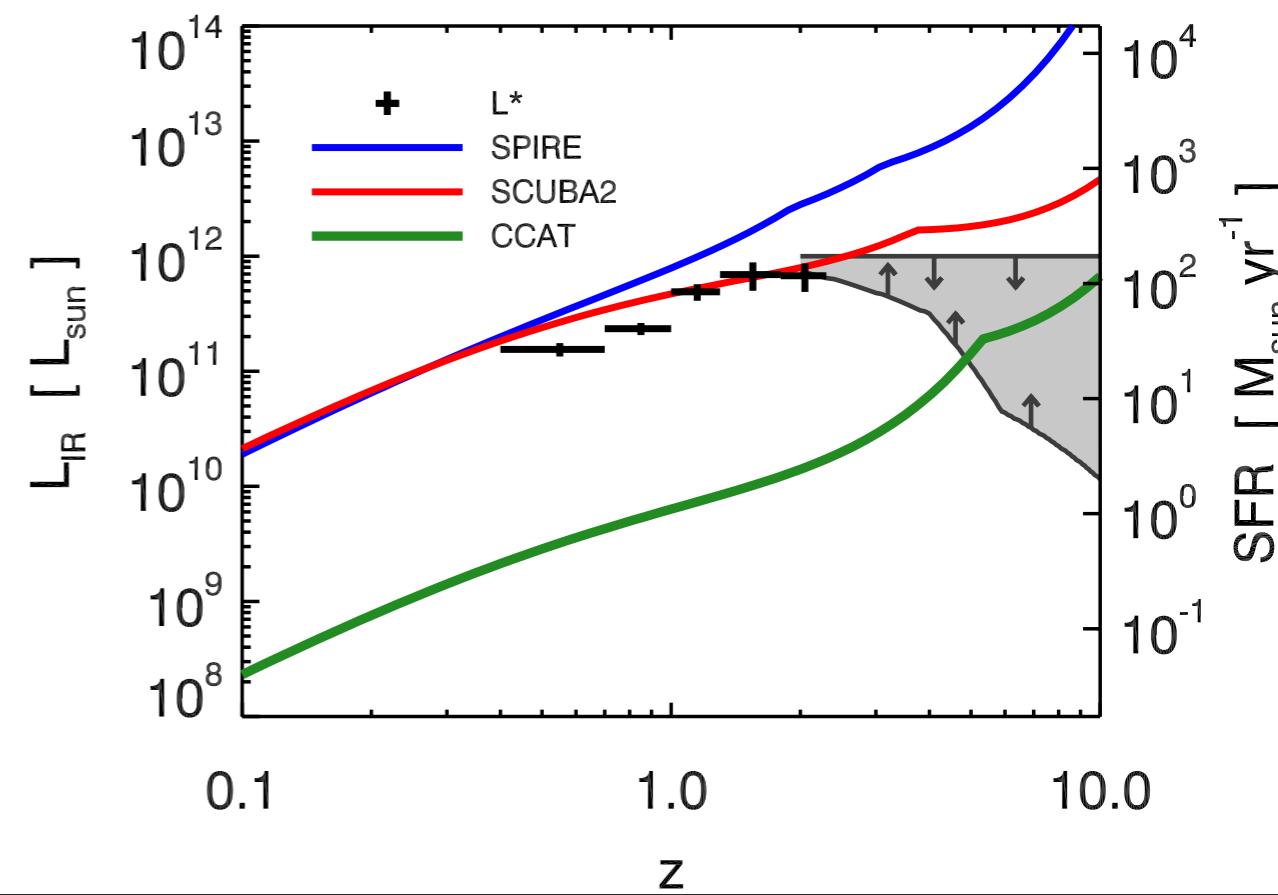
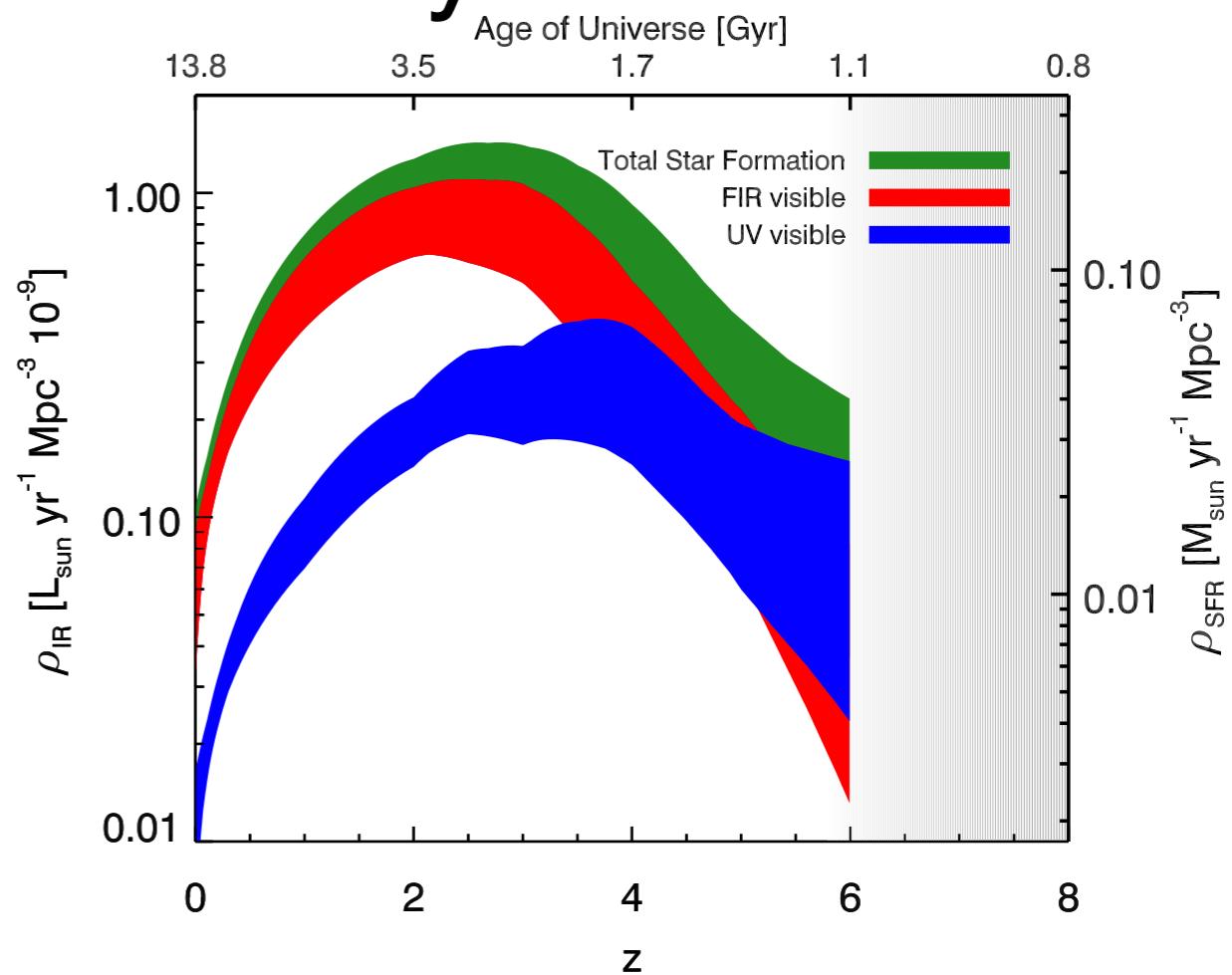


Instrument	[μm]	aperture [m]	FWHM [arcsec]
Spitzer/IRAC	3.6-8	0.85	2
Spitzer/MIPS	24	0.85	6
Herschel/PACS	70	3.5	5.2
Herschel/SPIRE	250	3.5	18
SPT	1400	10	70
SCUBA	450	15	8
SCUBA	850	15	15
LMT	1100	30 (50)	10 (6)
CCAT	350	25	3.5
CCAT	850	25	8.5



CCAT Extragalactic Survey #1: Directly Measure the Cosmic Star Formation History

- Resolve the 350 μm background into discrete sources in 2 deg 2 COSMOS field. (~1000 hours)
- Get 850 μm for photo-z, T_d , and L_{IR} .
- Get optical/IR spectroscopy (Ly-a, H-a) from Keck and VLT → Should get ~90% of sources. Chase remaining 10% with ALMA.
- Measure the star formation history, constrain models, find interesting sources, inform reionization.
- Requires:
 - 350 and 850 μm cameras on CCAT
 - followup with 10m optical telescopes (~20 nights)
 - followup with ALMA (~1 hour per source?)

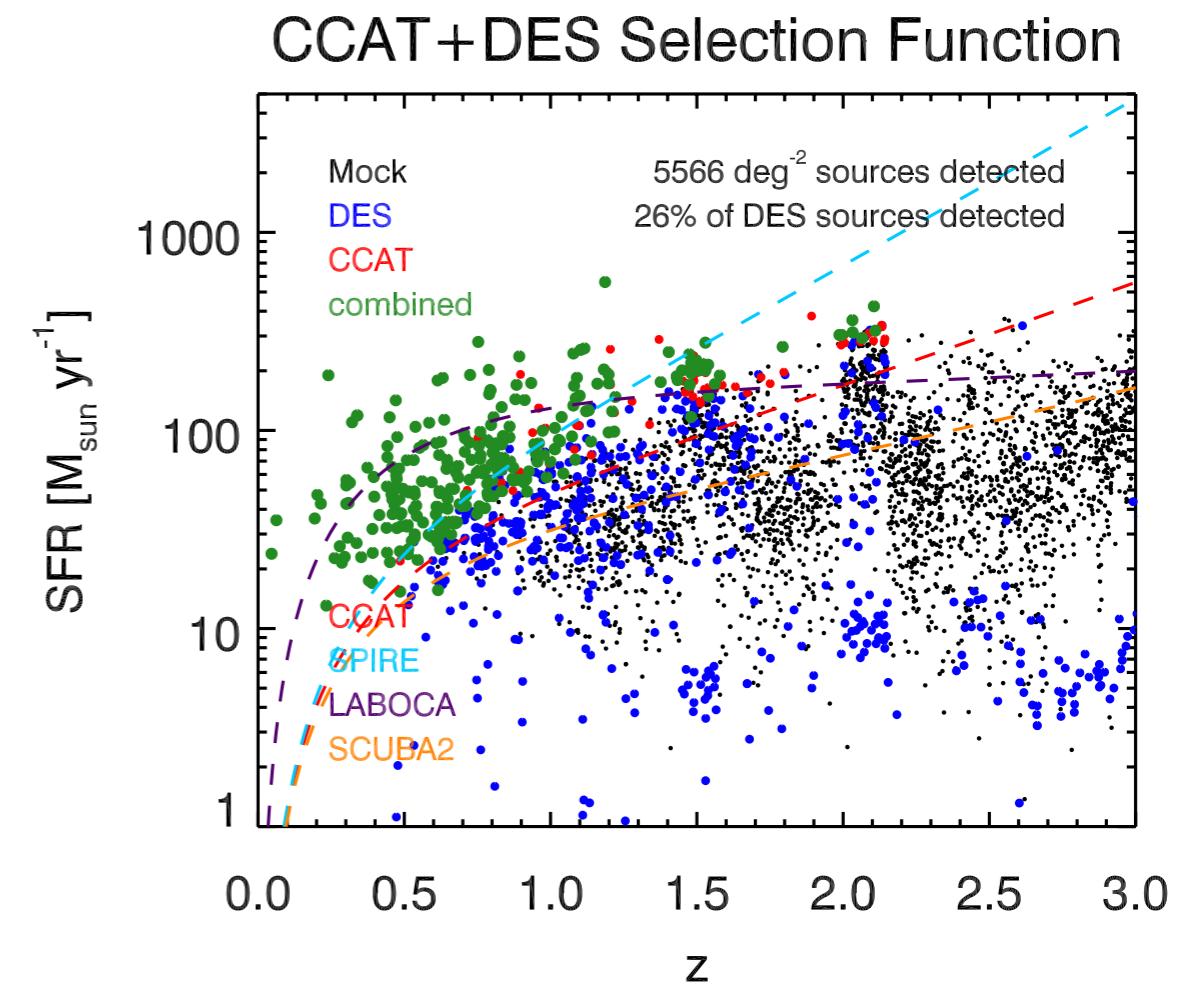




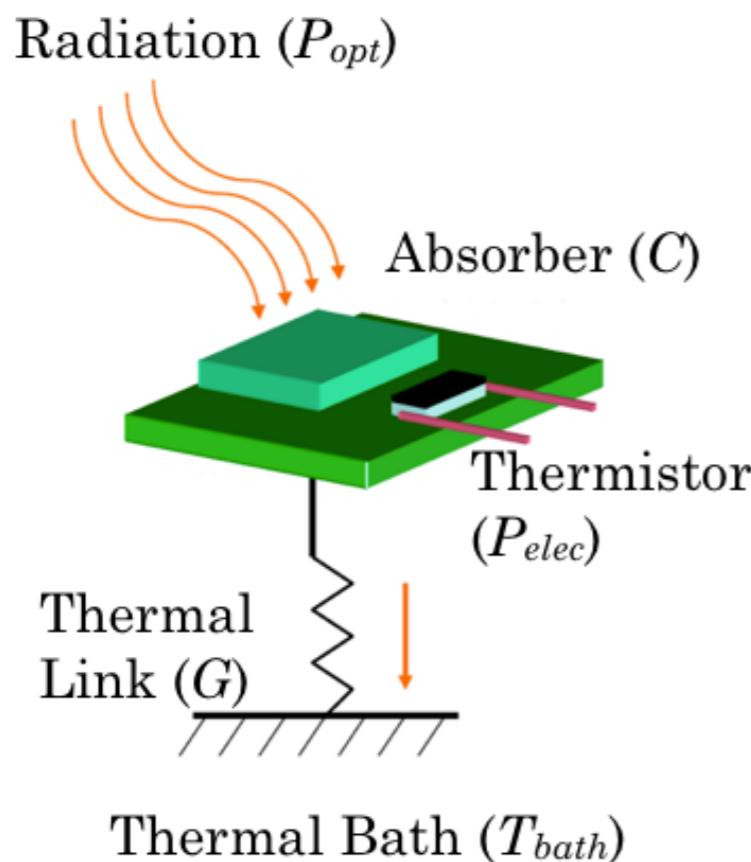
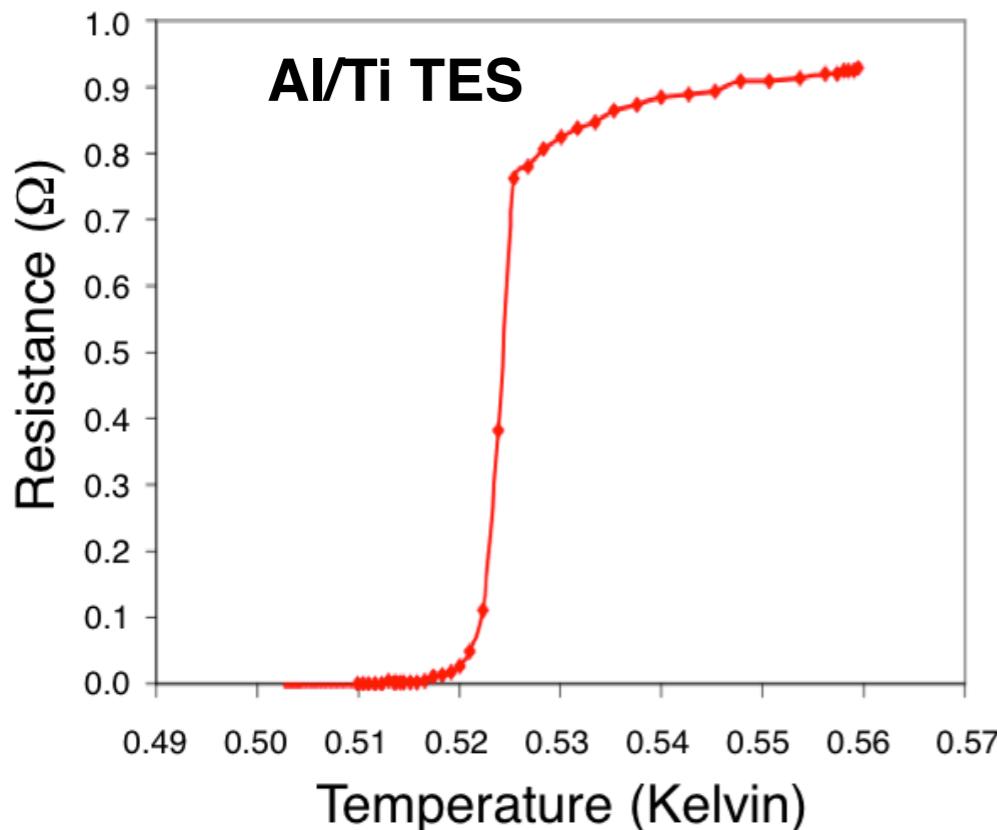
CCAT Extragalactic Survey #2:

Wide field object-oriented lower z astronomy (and some fluctuations)

- Use bad weather time to map \sim 2000 deg² SPT/DES/LSST southern sky at 350 and 850 μ m in 1000 hours
- Provide a submm flux for every optical galaxy at $z < 0.5$ in the southern sky.
- Detect \sim 25% of all DES sources
- FFT sky, get power spectrum,
- Find lensed sources.
- Link up with powerspectrum from SPT.
- Enable stacking of optical galaxies.



Superconducting Transition Edge Sensor (TES)



Bolometer Design Properties:

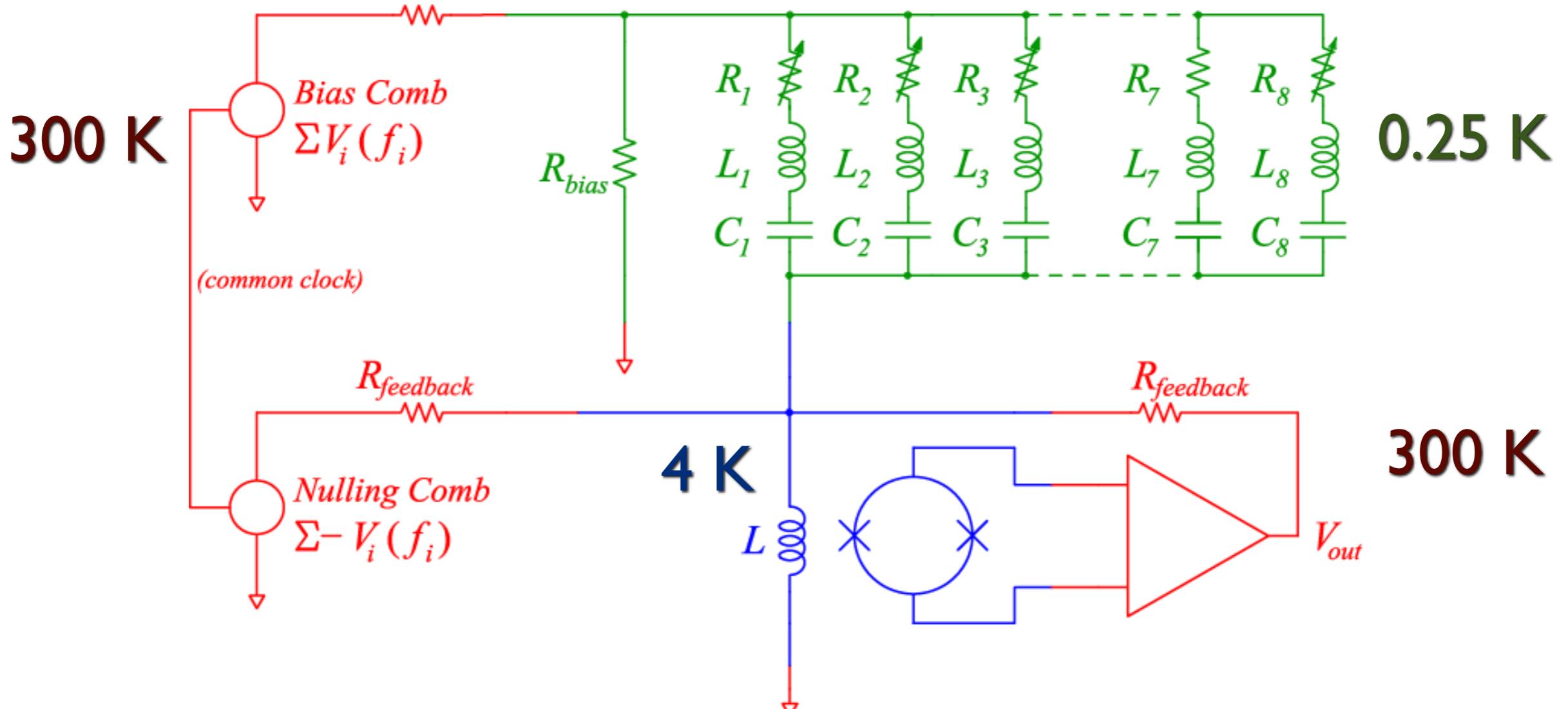
- Thermistor provides electrical power to balance optical power on bolometer:
$$P_{opt} + P_{elec} = \int_{T_{base}}^{T_{bolo}} G(T) dT$$
- Electrical feedback determined by slope of $R(T)$ curve, parameterized by a parameter:
$$\alpha = \frac{T}{R} \frac{dR}{dT} \quad \begin{aligned} TES &\sim 20-1000 \\ NTD &\sim 3-10 \end{aligned}$$
- Can define a “loop gain” in analogy to electronic feedback circuits:

$$\mathcal{L} = \frac{\alpha P_{elec}}{G T_b} \quad \begin{aligned} TES &\sim 20-1000 \\ NTD &\sim 1-5 \end{aligned}$$

- Increased loop gain improves the linearity (in responsivity) and speed of the detector:

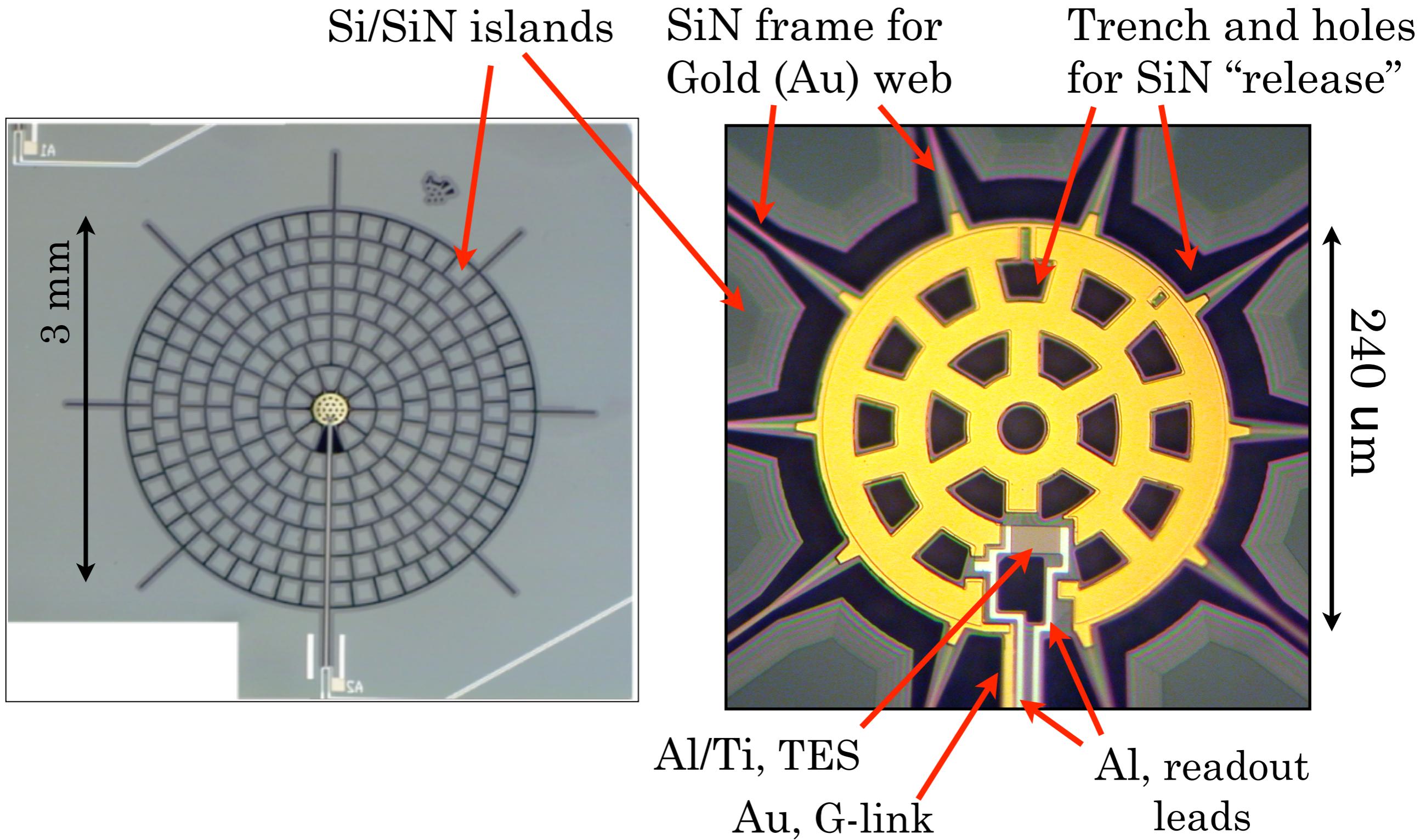
$$S_I = \frac{\delta I}{\delta P} = \frac{-1}{V_b} \frac{\mathcal{L}}{1 + \mathcal{L}} \quad \tau = \frac{\tau_0}{1 + \mathcal{L}} = \frac{C/G}{1 + \mathcal{L}}$$

Frequency Domain Multiplexing (fMUX)

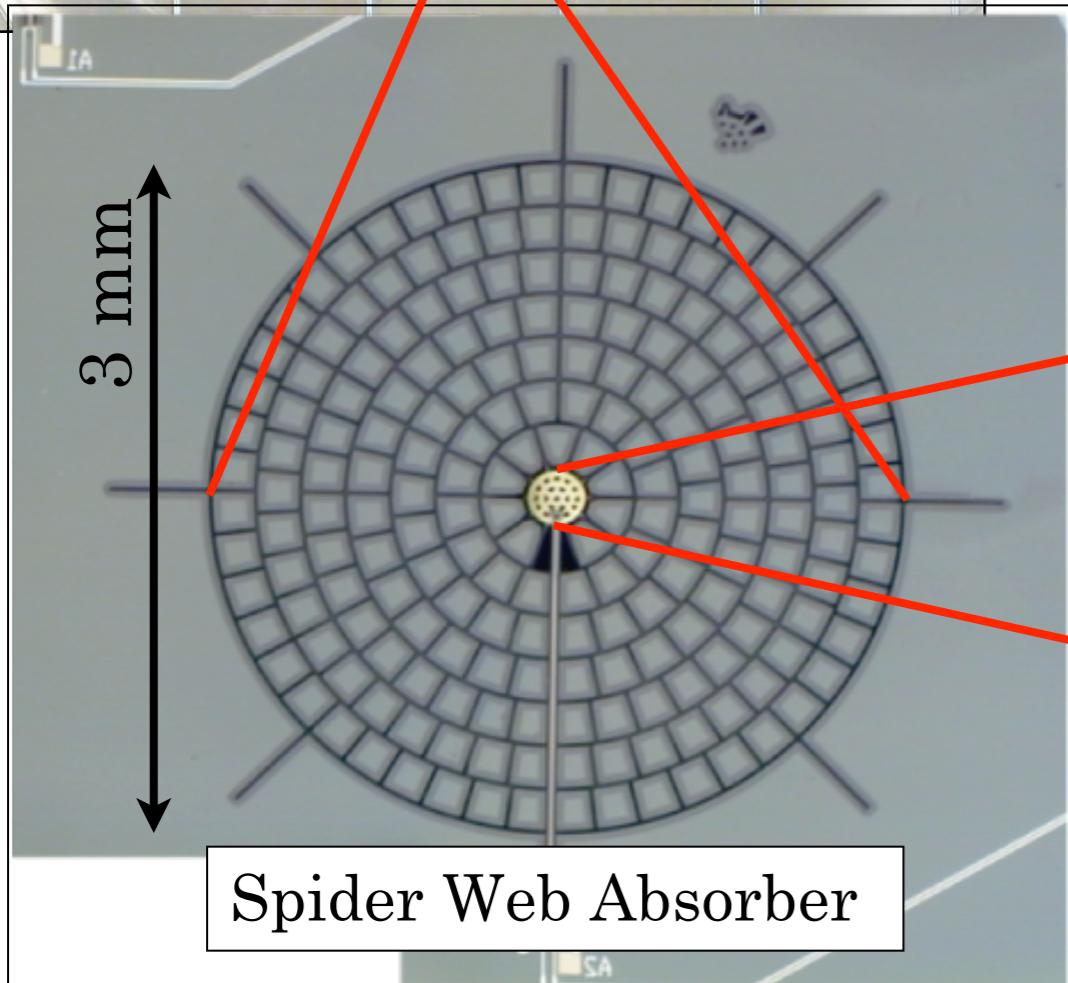
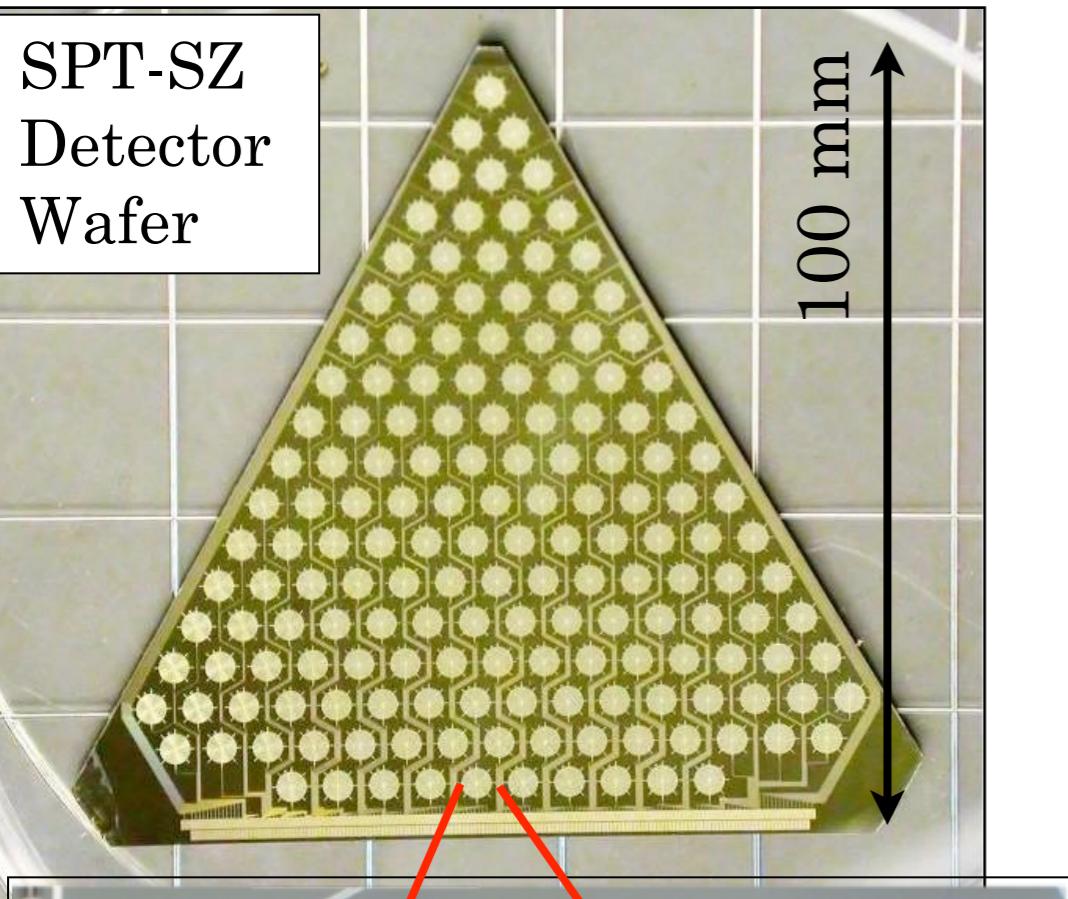


- Developed current summing fMUX at UC-Berkeley and Lawrence Berkeley Labs (LBL)
- AC Bias row of detectors with comb of frequencies between 300-950 kHz at RLC filter resonances: $2\pi f_{\text{filt}} = w_{\text{filt}} = 1/(LC)^{1/2}$
- Crosstalk determined by Q of LC resonance (designed to be < 1%): $\delta w_{\text{filt}} = R/L$, therefore $Q = (L/RC)^{1/2}$

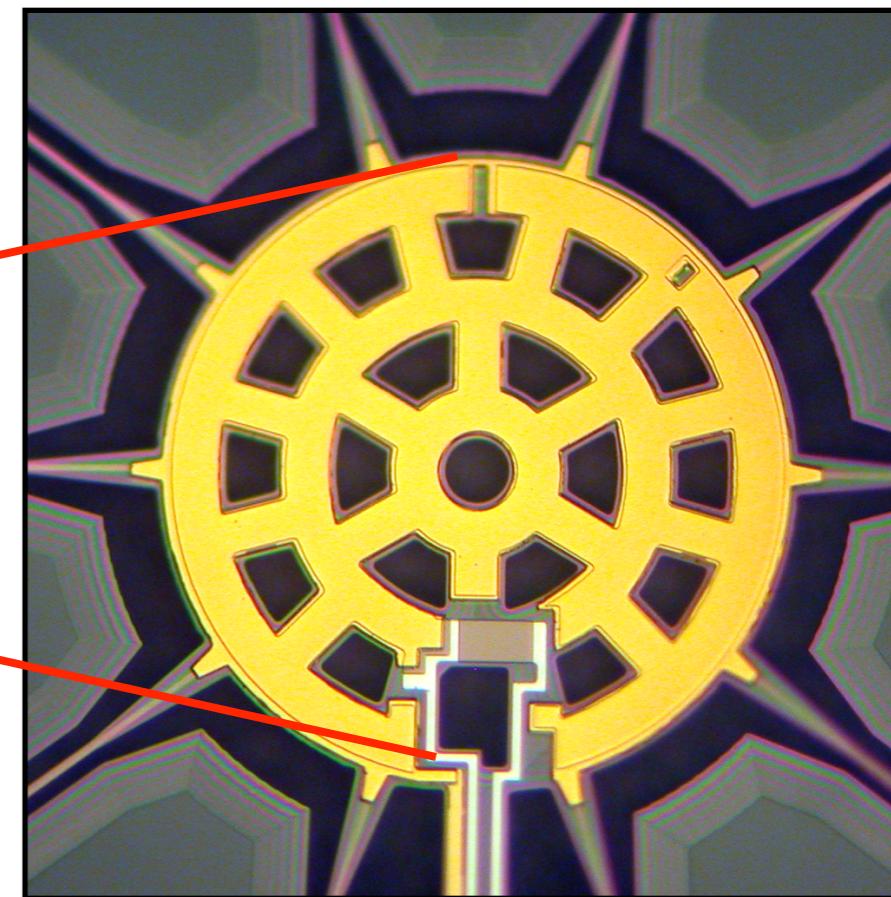
SPT-SZ Bolometer (2007-2011)



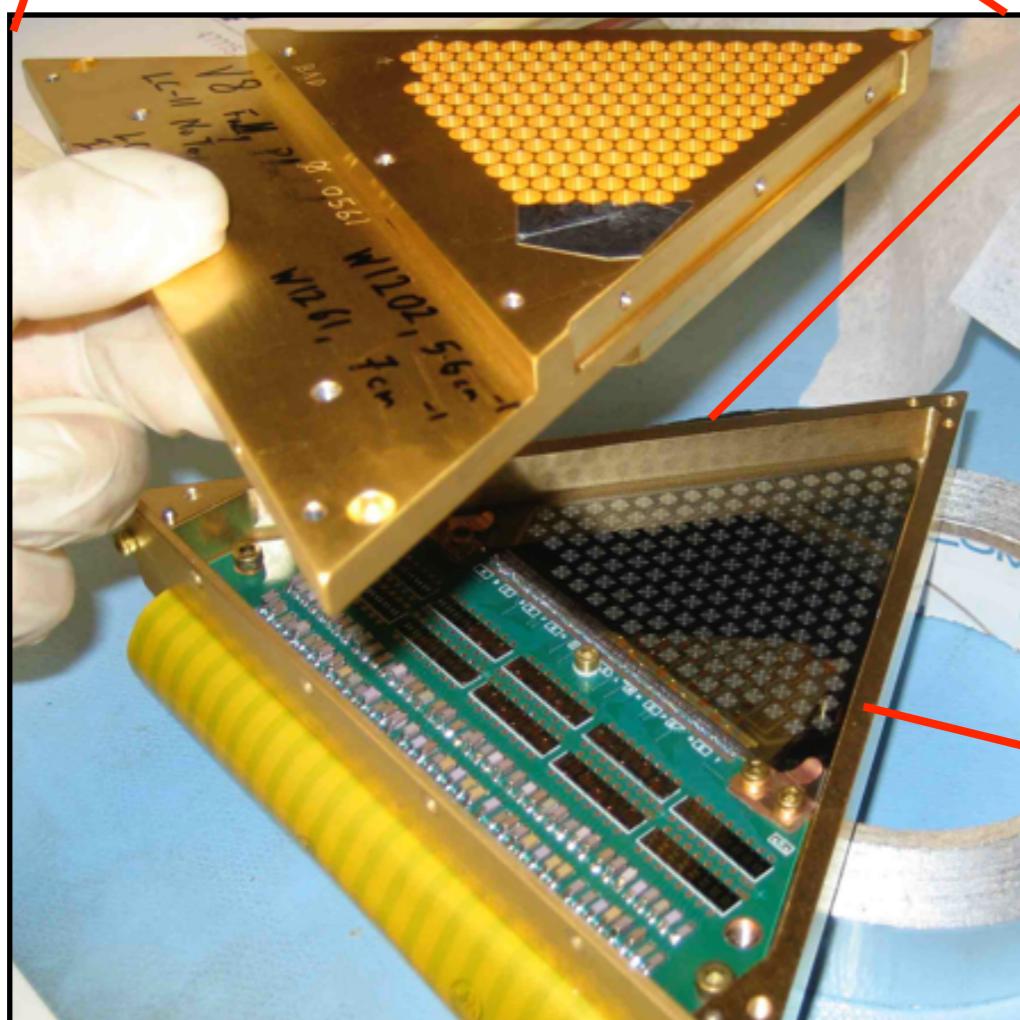
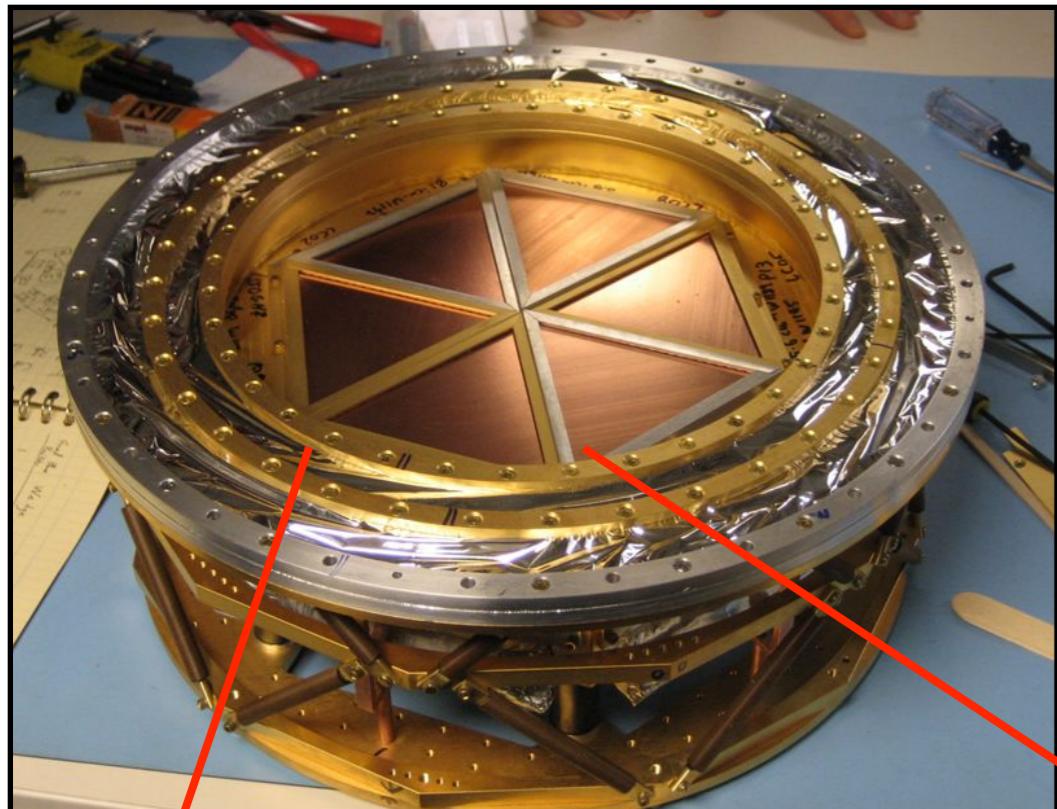
SPT-SZ Bolometer Array (2007-2011)



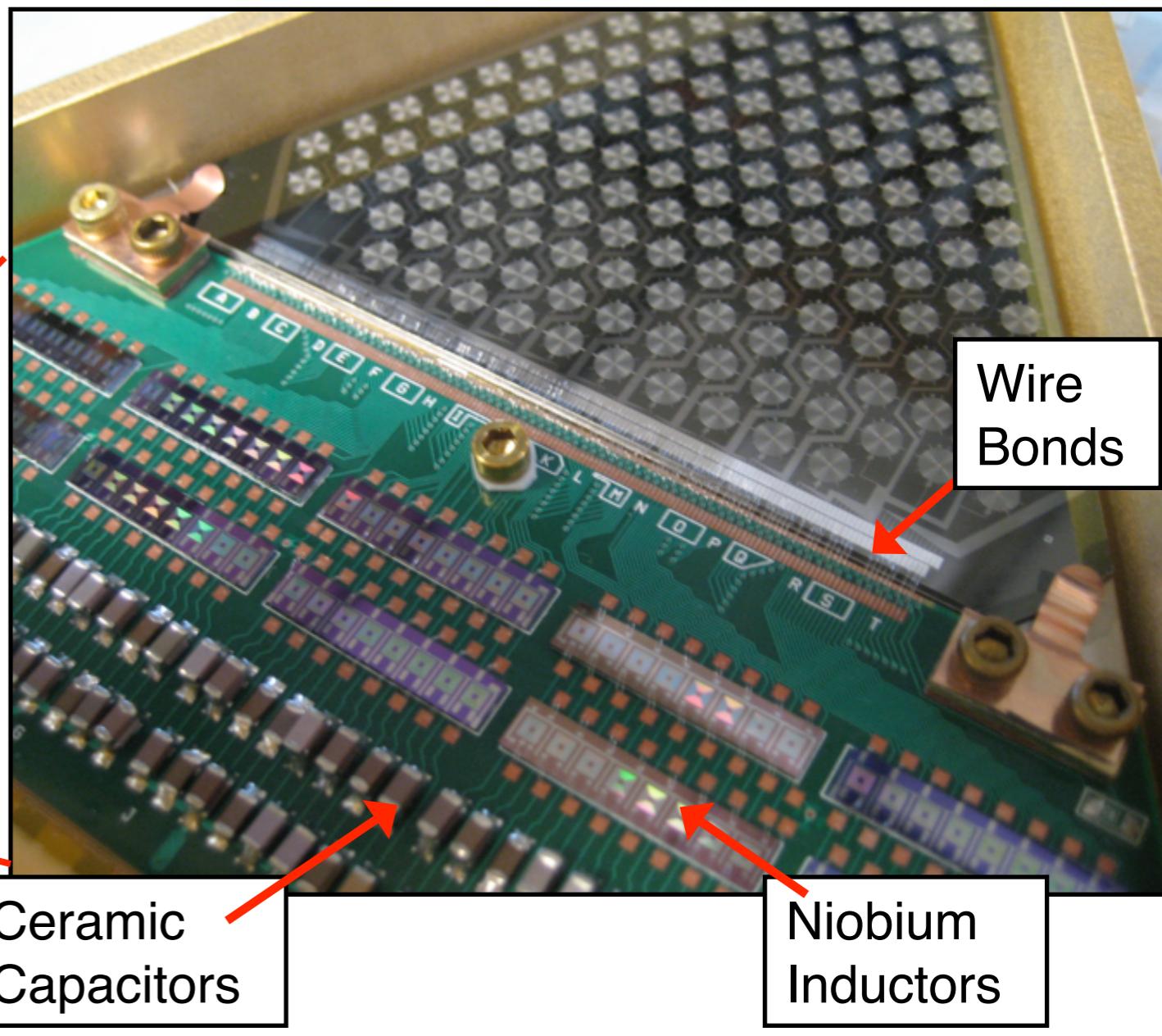
- Fabricated by Erik Shirokoff at UC-Berkeley
- 160 bolometers per wafer
- Al/Ti bi-layer (TES) with $T_c = 0.55$ K
- Operates at $L \sim 20$ with $t_{\text{TES}} \sim 1$ msec, $t_{\text{optical}} \sim 10-15$ msec
- Wafer thickness equal 1/4 observing wavelength



SPT-SZ Detector Module and LC Board

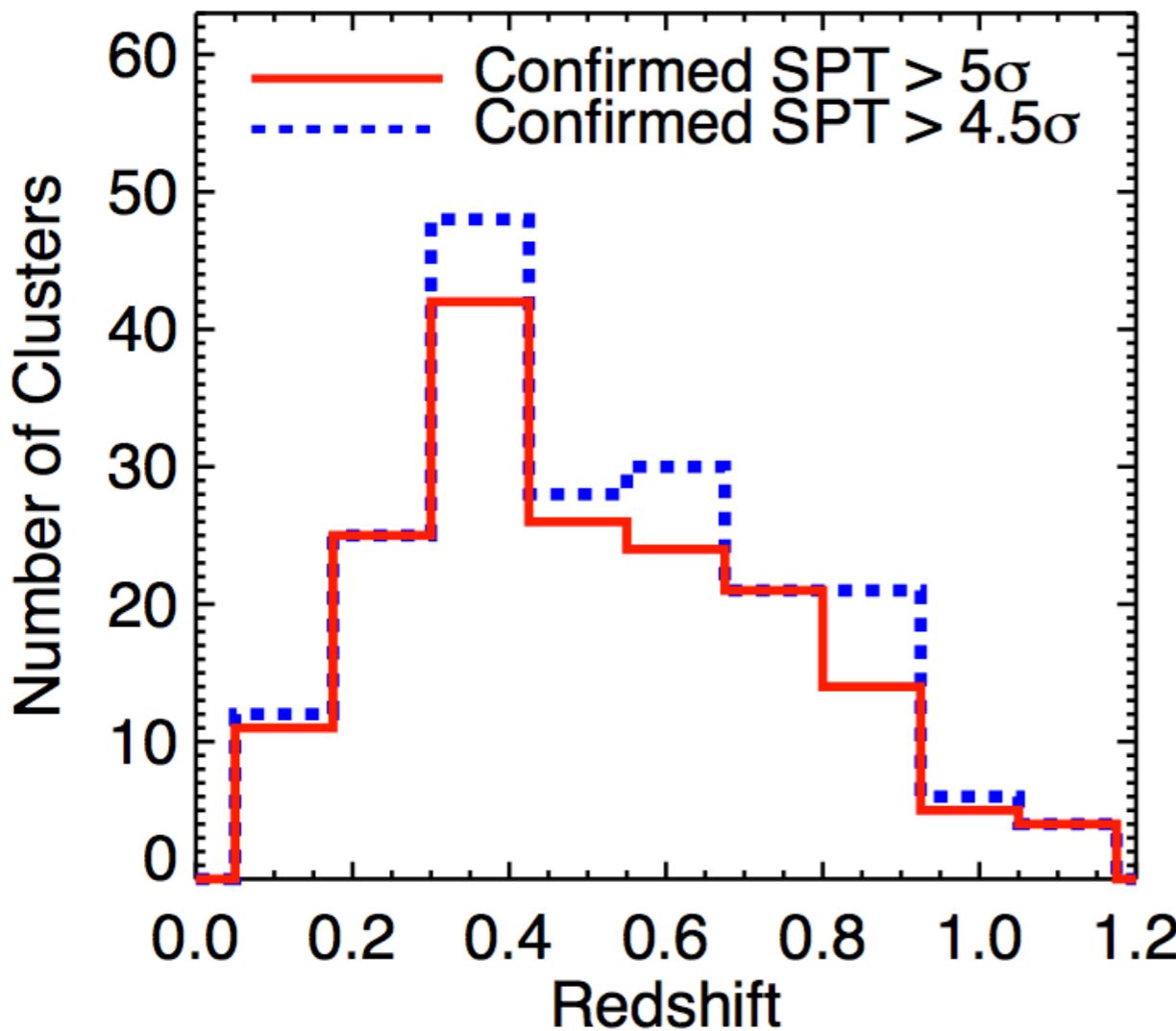


- Wafer wire-bonded to circuit board with LC circuit, which sets each bolometer's resonant frequency for frequency Multiplexing (fMUX)

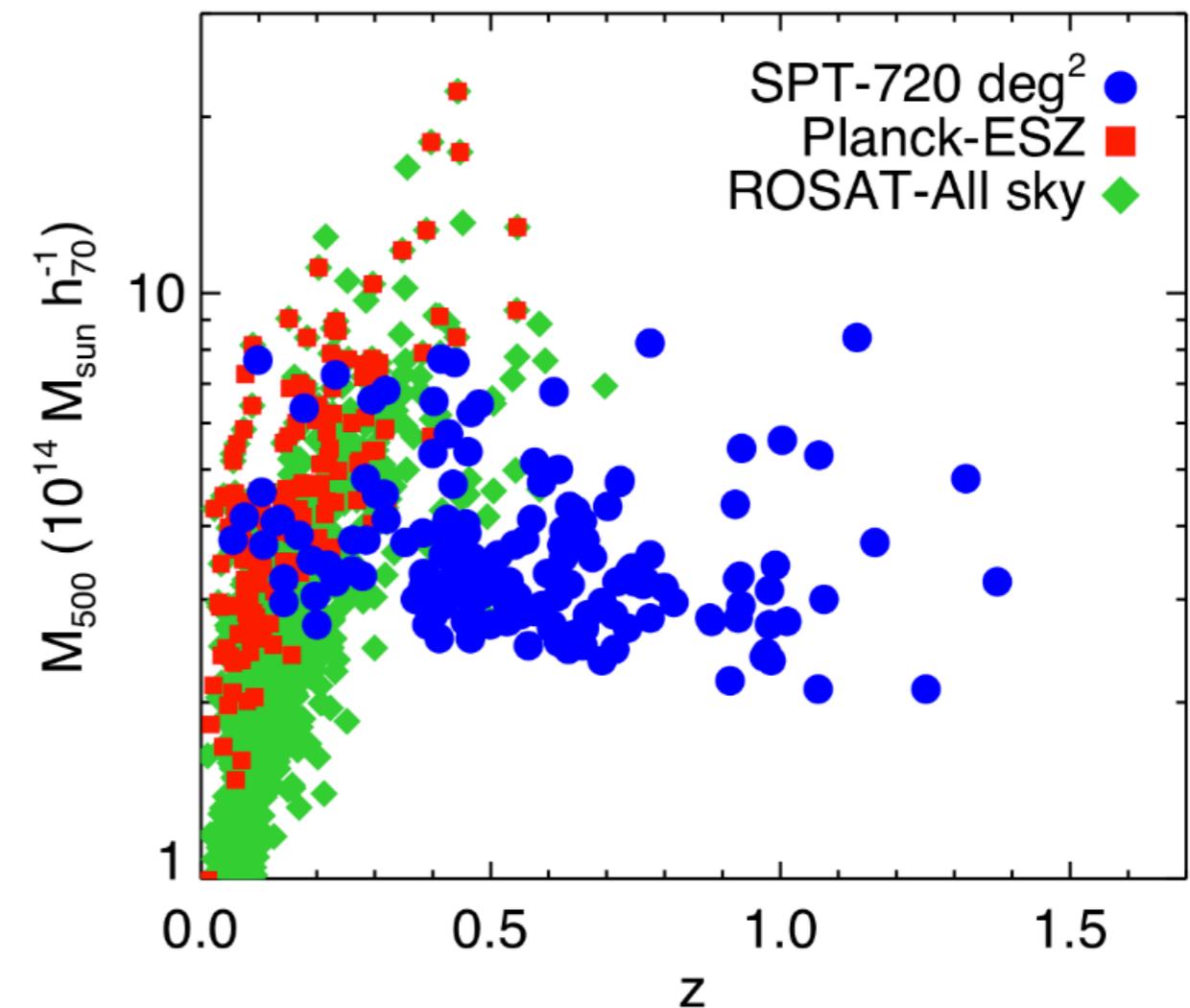


SPT SZ-Selected Galaxy Clusters

Redshift Histogram

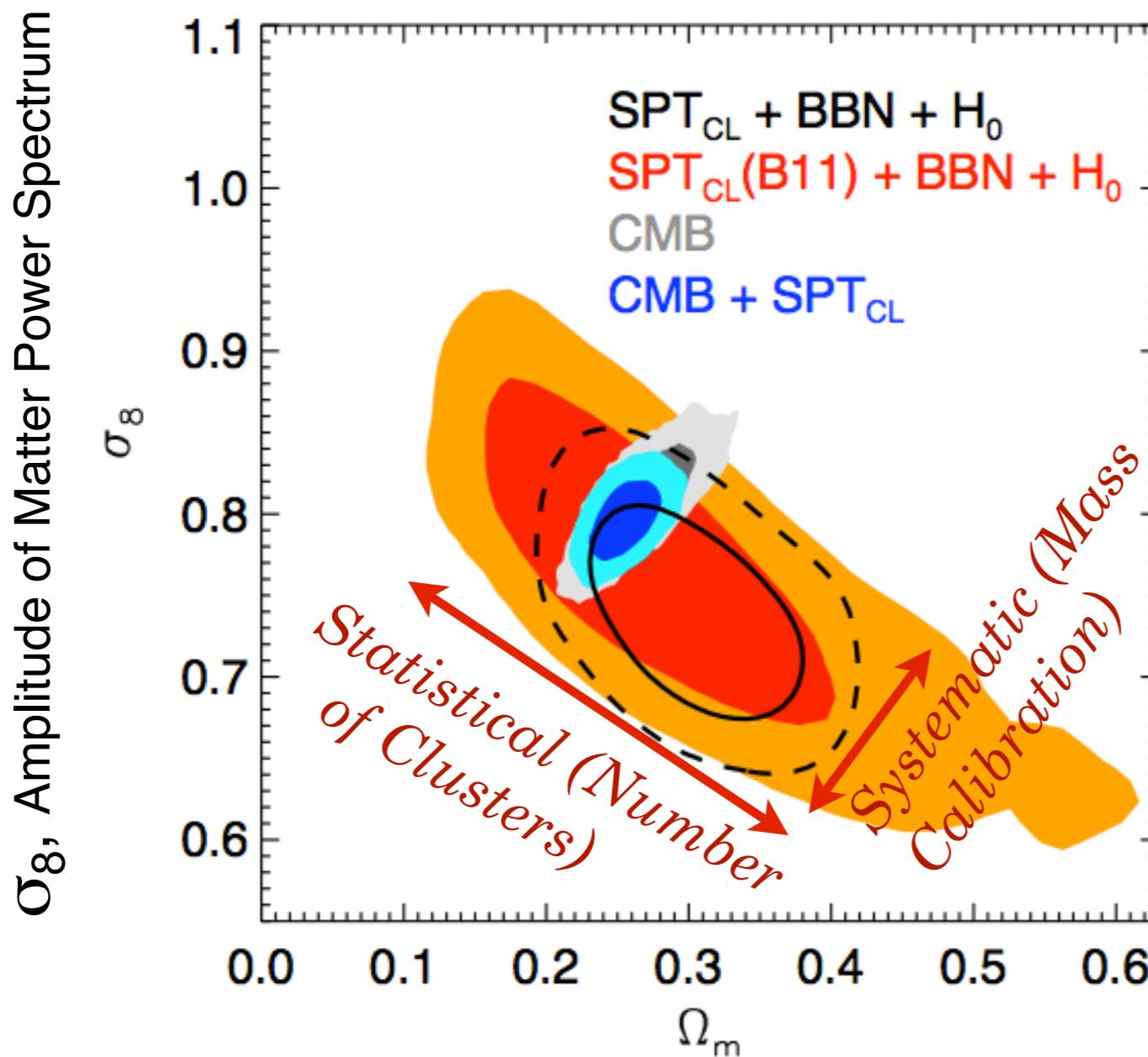


Mass vs Redshift



- confirmed > 450 clusters, $\sim 80\%$ newly discovered, $\sim 95\%$ purity at $S/N > 5$
- High redshift: $\langle z \rangle = \sim 0.6$
- Mass threshold independent of redshift: $M_{500}(z=0.6) > 3 \times 10^{14} M_{\odot}/h_{70}$

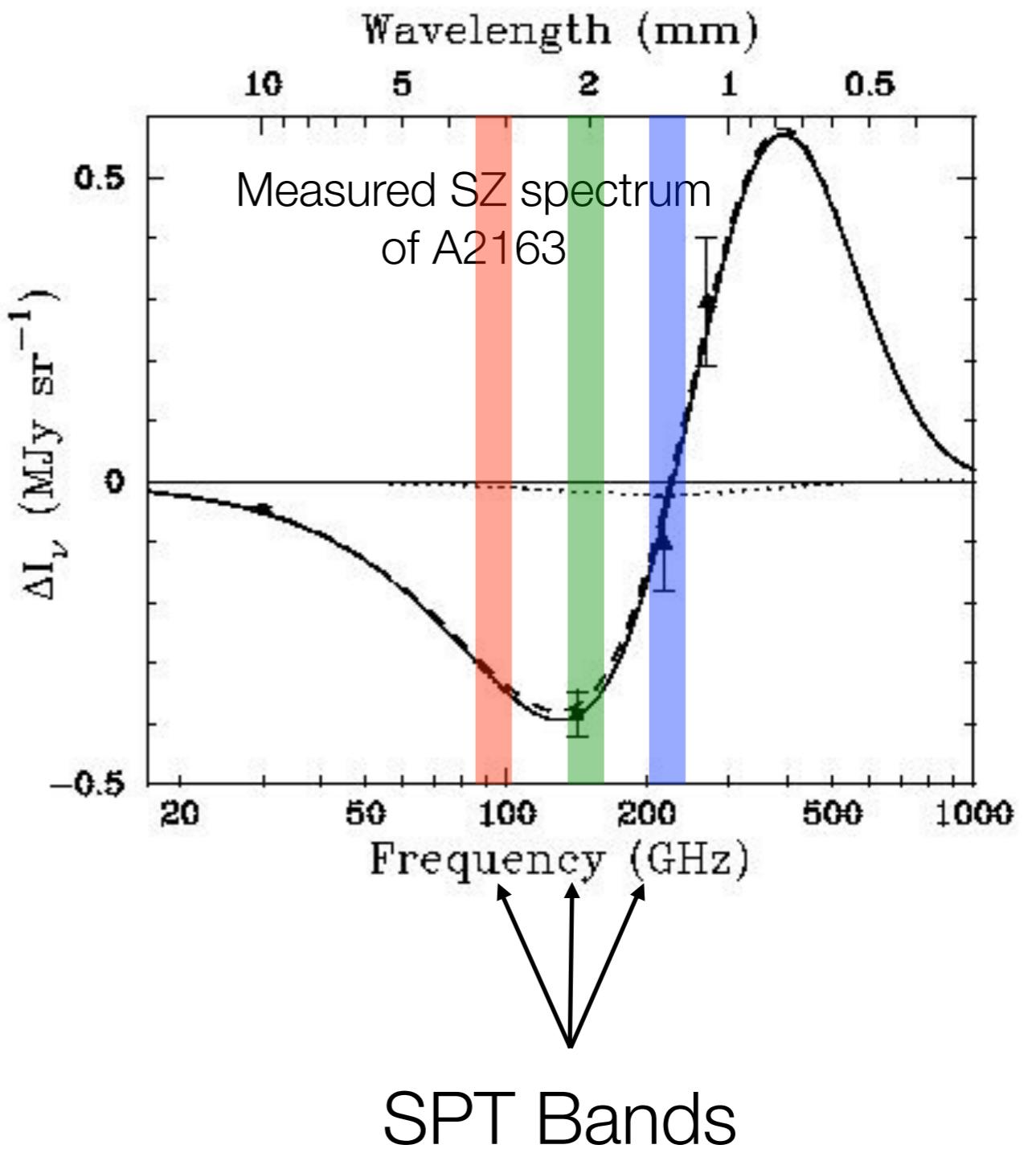
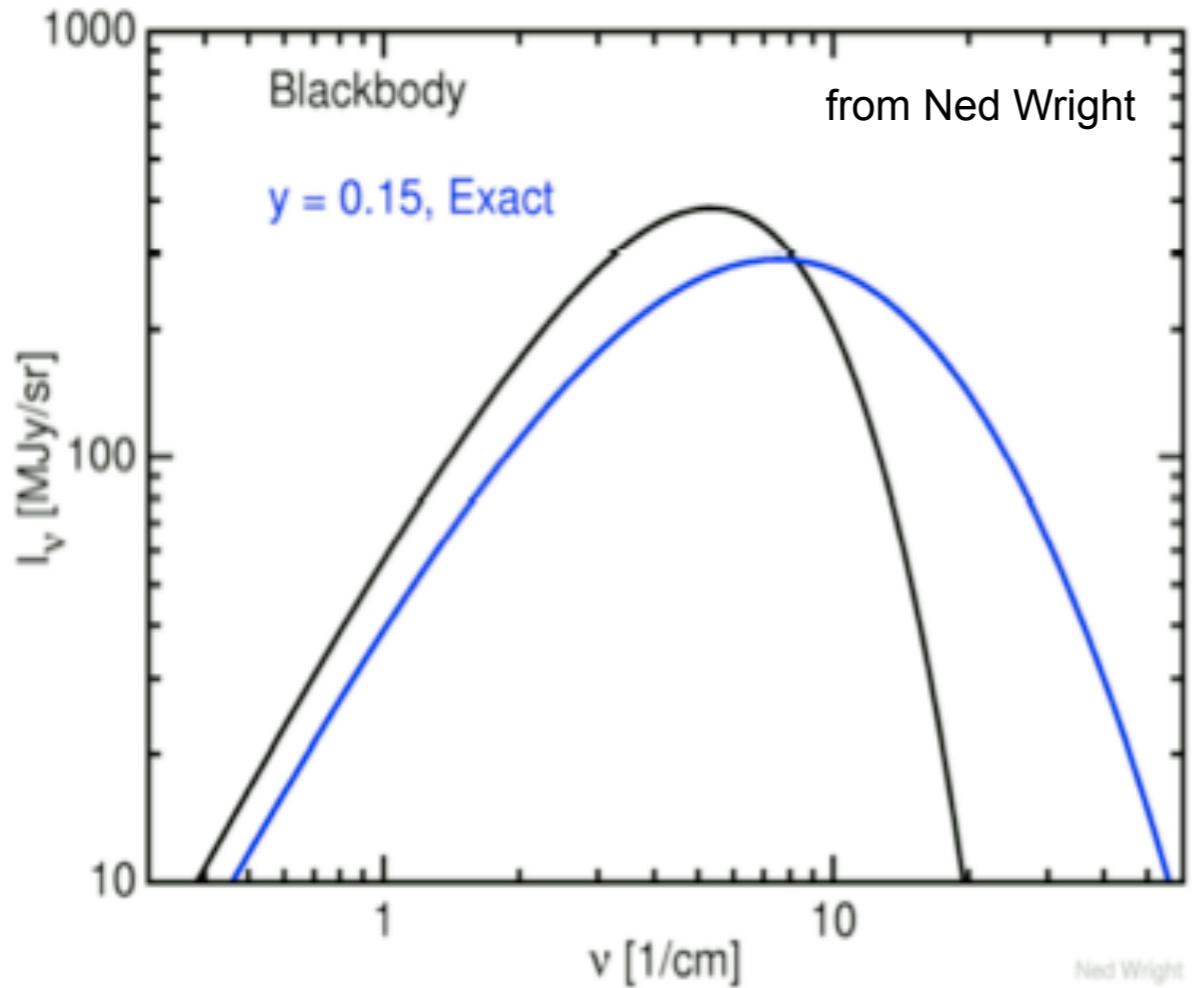
Λ CDM Constraints: Now use 100 clusters (Reichardt et al. 2012)



- SPT increased cluster sample by $\sim 5x$ in Reichardt et al. (2012) improving constraints in σ_8 - Ω_m plane by 1.8x in area
- ***In direction orthogonal to CMB constraints, cluster constraints limited by mass calibration***

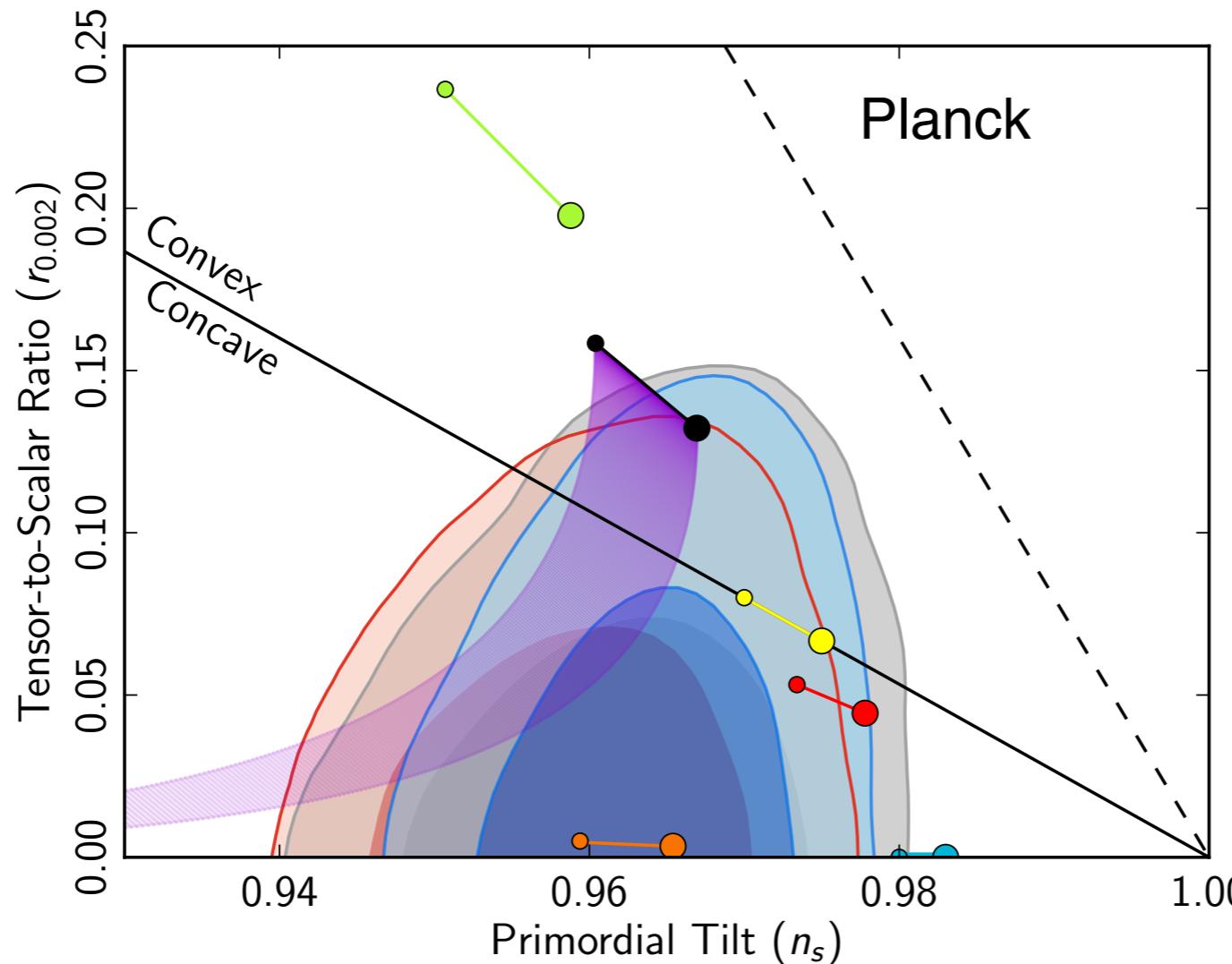
Reichardt et al 2012, arXiv:1203.5775

Sunyaev-Zel'dovich Effect



Constraints on Inflation

the energy scale of inflation



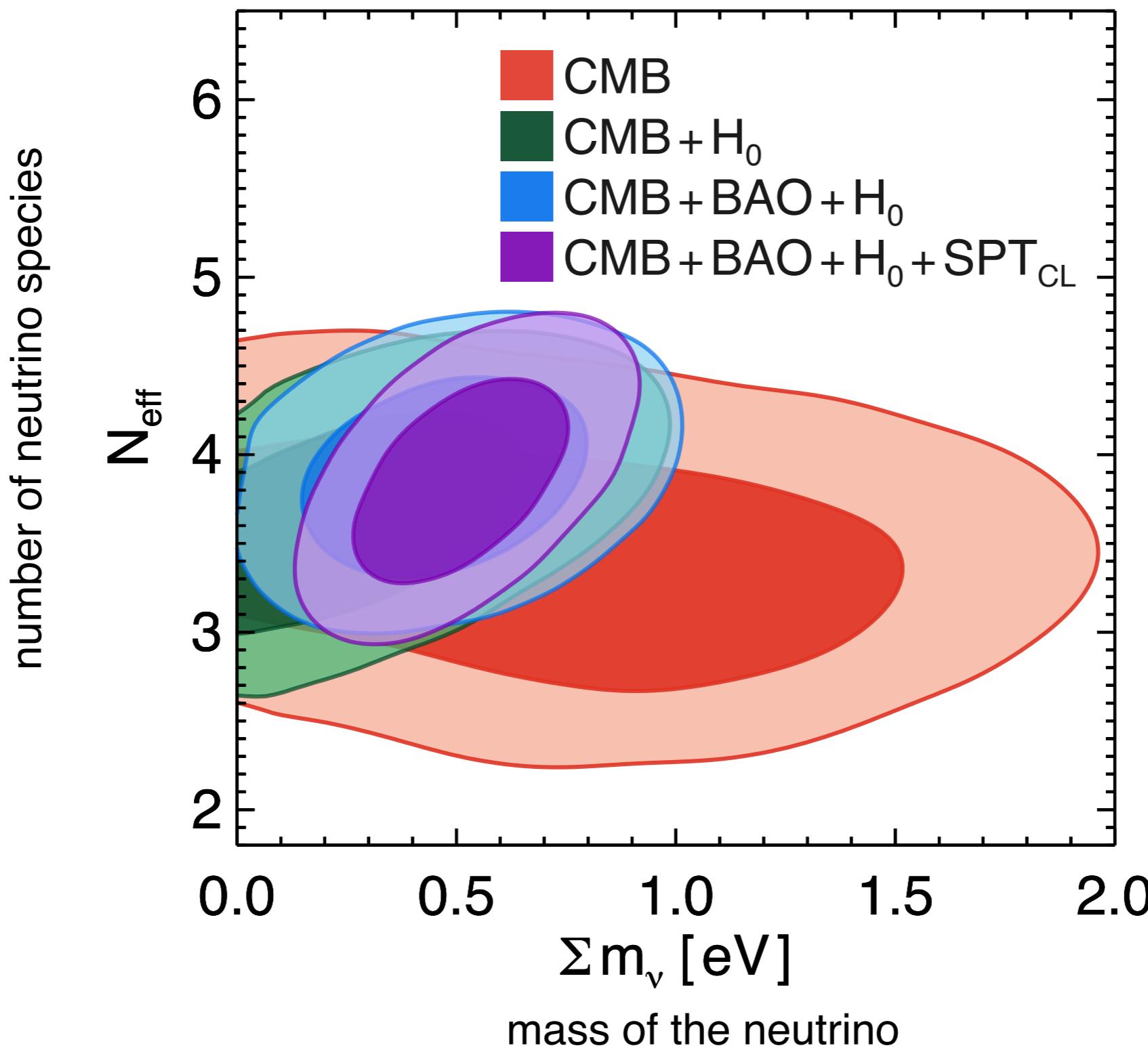
$$r \equiv \frac{\Delta_h^2}{\Delta_R^2}$$

(tensor/scalar) ratio

slope of the CMB damping tale
inflation predicts $n_s \neq 1$

$$\Delta_R^2(k) = \Delta_R^2(k_0) \left(\frac{k}{k_0} \right)^{n_s - 1}$$

Constraints on Neutrinos



Primary CMB anisotropy

